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HOW TO ASSESS THE SURVIVABILITY OF U.S. ICBMs

Bruce W. Bennett

SUPPORTED BY A GRANT FROM
THE FORD FOUNDATION

A SERIES IN INTERNATIONAL
SECURITY AND ARMS CONTROL

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PREFACE

In late 1978, The Ford Foundation provided grants to The Rand Corporation and several university centers for research and training in international security and arms control. At Rand, the grant is supporting a diverse program. In the Rand Graduate Institute, which offers a doctorate in policy analysis, the grant is contributing to student fellowships for dissertation preparation, curriculum development, workshops and tutorials, and a series of visiting lecturers. In Rand's National Security Research Division, the Ford-sponsored projects are designed to extend beyond the immediate needs of government sponsors of research by investigating long-term or emerging problems and by developing and assessing new research methodologies. The grant also is being used to fund the publication of relevant sponsored research that would otherwise not be disseminated to the general public.

All research products are being made available to as wide an audience as possible through publication as unclassified Rand Reports or Notes or in journals. The Rand documents may be obtained directly or may be found in the more than 330 libraries in the United States and 35 other countries that maintain collections of Rand publications.

This report derives from the author's doctoral dissertation prepared for the Rand Graduate Institute. It is one product of the author's work at Rand in assessing the U.S. strategic force posture. Much of that work has concentrated on the potential importance of uncertainties in such assessments.[1]

For a number of years, ICBM survivability has been a major and growing concern in the U.S. strategic debate, all the more so because of persistent increases in Soviet counterforce capabilities. Within the United States, analysis has consistently shown the Soviet threat to be severe, though many authors have indicated that a variety of operational problems faced by the Soviet forces may mitigate the apparent vulnerability of our ICBMs. At the same time, alternative ICBM basing schemes are being developed in the hopes of providing some assured level of ICBM survival. This report deals with each of these issues, developing in detail the relationships involved in ICBM survival, and showing how uncertainties in each aspect can influence the assessment of survivability. An accompanying volume of Appendixes,

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[1]See, for example, Bruce W. Bennett, *Fatality Uncertainties in Limited Nuclear War*, The Rand Corporation, R-2218-AF, November 1977.

R-2578-FF, provides more technical detail on several of these issues. This work should prove to be of interest both to strategic planners who are concerned about the policy implications of ICBM survivability and to analysts throughout the community who are interested in some of the details behind the ICBM survivability question.

SUMMARY

The survivability of U.S. strategic forces has been an issue since the early 1950s.[1] At that time the strategic forces (primarily bombers, even through the early 1960s) were not protected from nuclear effects, and serious questions about the reliability of tactical warning arose (especially after Sputnik); the result was a disturbing uneasiness over whether we could launch our forces promptly in response to an attack. That anxiety eased in the early 1960s, when ballistic missile warning systems were developed and ICBMs were emplaced in hardened silos to protect them from nuclear effects in case of attack. Minuteman ICBMs proliferated to such an extent (1000 missiles) that it seemed unlikely that a survivability problem would develop even through the late 1960s. But, the specter of ICBM vulnerability rose again in the early 1970s with the Soviet development of MIRVed ICBMs, which also had a much improved accuracy. Still, the interval between Soviet development and full deployment is so long that the threat to the U.S. ICBM force does not appear substantial today; almost all observers anticipate no significant *potential* vulnerability for Minuteman before the mid-1980s. It would be unwise, however, to take comfort in the possibility that this potential vulnerability may not become real and serious, at least for several years; it is critical to confirm or deny it now so that a solution can be sought, if necessary, because we too would have to undergo a very long lead-time to reshape our strategic posture. One impediment is the sharp variance in the survivability estimates available to the defense community; a more rigorous and reliable methodology for this kind of assessment is clearly needed.

A factor often cited as mitigating ICBM vulnerability is the uncertainty inherent to most of the parameters involved in survival calculations. For example, Secretary of Defense Brown has said, "The seemingly paradoxical situation that results from these technological and strategic considerations is that, in the early 1980s, we will not have much confidence that more than a small percentage of our silo-based missiles can survive a Soviet preemptive attack. But the Soviets could not be at all confident of destroying the bulk of our missiles."[2]

[1]The first major concern in this area originated with a Rand bomber-basing study: A. J. Wohlstetter, F. S. Hoffman, R. J. Lutz, and H. S. Rowen, *Selection and Use of Strategic Air Bases*, The Rand Corporation, R-266, April 1954.

[2]Harold Brown, *Department of Defense Annual Report, Fiscal Year 1979*, February 1978, p. 106.

However, uncertainty is present in almost all aspects of life, and at least some uncertainty or risk is acceptable in any venture, especially if the stakes are high enough. Therefore, before we can depend on uncertainty alone to deter a Soviet counterforce strike, it is first necessary to parameterize the factors that cause the uncertainty in ICBM survivability, and thus determine its probable effects.

Once all of the parameters and uncertainties are combined, it is possible to develop complete survivability distributions like those shown in Figs. 36 and 37. These distributions show the cumulative probability of a Soviet attack achieving at most a given kill probability against U.S. ICBMs, and thus specify the confidence with which survivability can be expected. These figures suggest that, from a U.S. perspective, the Soviets do indeed face a very high risk in any attack against the U.S. ICBMs.

ASSESSING ICBM SURVIVABILITY

ICBM survivability can be broken down into four components: (1) the probability that a target will be destroyed *if* a single warhead arrives and detonates in its vicinity (the single-shot kill probability or SSPK), (2) the effect of multiple warheads arriving and detonating near the target, (3) the probability that a warhead arrives and detonates at the target, and (4) the probability that a warhead survives fratricide to detonate. Even though an analysis of ICBM survivability cannot be complete unless all four of these components are discussed, such analysis is almost nonexistent in the strategic literature;[3] indeed, the traditional model of ICBM survivability focuses on the first component, ignores the last one, and deals only partially with the other two.[4] Even when the analysis addresses these components, it omits many of the important factors they involve. For example, though the SSPK is actually a function of eight parameters, most

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[3]A possible exception is the article by John Steinbruner and Richard Garwin, "Strategic Vulnerability: The Balance Between Prudence and Paranoia," *International Security*, Summer 1976, pp. 138-181. However, that article apparently assumes a strict compounding function for multiple shots without developing the assumptions here, and tends not to deal explicitly in computational form with many of the tradeoffs, as shown in James L. Foster, "Essential Equivalence: What Is It and How Should It Be Measured," *Equivalence, Sufficiency, and the International Balance*, Proceedings of the National Security Affairs Conference, Office of the Assistant Secretary of Defense (International Security Affairs) and the National Defense University, August 1978, pp. 41-43.

[4]The traditional model is applied in this way in the well-known articles by Kosta Tsipis, *Offensive Missiles*, SIPRI Stockholm Paper 5, 1974, and Robert L. Leggett, "Two Legs Do Not a Centipede Make," *Armed Forces Journal International*, February 1975, pp. 30-32.

analyses consider only target hardness, warhead yield, and impact CEP (circular probable error). The traditional model thus leaves out many factors that determine ICBM survivability.

Once each of those components and its influence on survivability are understood, the effect of uncertainty can be parameterized. The resulting parameters differ from each other, in at least some ways, and those differences must be taken into account in developing a notion of uncertainty. Further, uncertainty itself has three components: random variations, uncertainty in the mean value of a parameter, and unknown aspects of a parameter. Three general problems beset any attempt to take all of those factors into consideration. First, because many of the basic parameters are interrelated, uncertainty in one increases the uncertainty in others.[5] Second, some of the "basic" relationships are so complex that, while it is possible to model them in part, they cannot be reasonably included in a net assessment of ICBM survivability.[6] Finally, our lack of knowledge in many areas prevents us either from being able to parameterize an effect (such as EMP) or from being able to develop the "true" uncertainty distribution of a parameter. Consequently, the methodology and parameter values used herein are often approximations, representing an initial attempt to pull this broad area together.

In analyzing the SSPK component of survivability, it is found that, depending upon the uncertainty distributions chosen, SSPK can be highly uncertain from either the U.S. or the Soviet point of view (see Figs. 20 and 21). Those results are based on the uncertainty levels assumed in Table 2. SSPK is a function of three general factors: target vulnerability, warhead destructiveness, and warhead accuracy. The parameters in the first two factors are assumed to exhibit normal distributions in their uncertainty, with truncated distributions required in many cases to stay within the valid limits of the values for a parameter. The accuracy factor is associated more with a chi-square distribution for CEP, while different formulations are used for systematic bias, about which relatively little is known.

This report contends that the process of combining SSPK estimates into a multiple-shot kill probability (PK) for arriving and detonating warheads is not as simple as the traditional model assumes. In the traditional model, the SSPK values could simply be compounded into a PK, based upon a "cookie-cutter" damage function. More complete calculations must consider target-to-target and weapon-to-weap-

[5]See, for example, the analysis in App. C of height-of-burst uncertainty and its effect on accuracy.

[6]The difficulty in developing an adequate relationship for the deception multiplier (see App. F) is typical of this kind of problem.

on random variations, as well as the effect of earlier, "nonlethal" warheads in "softening" the target. Unfortunately, none of these effects are well parameterized, nor does there appear to be any simple way to do so; therefore, simple compounding of damage is used as a default option, recognizing that this choice introduces extra, unmeasured uncertainty in the final outcome.

The arrival probability of a warhead hinges on a number of factors, including prelaunch survivability, reliability, and penetration. If we assume a Soviet first strike against undefended U.S. silos, the arrival probability simplifies to include reliability only.[7] Arrival probability is important because a warhead obviously can do no damage unless it arrives and detonates at its target. A perceived problem in arrival probability is usually hedged against by assigning more than one warhead to each target (preferably from independent boosters) in order to "guarantee" that at least one does arrive and detonate. Uncertainty about reliability is due to the limited number of test shots that are possible, which provide insufficient data for accurately estimating the reliability of a warhead.[8] The attacker can usually solve some of the problems resulting from less than 100-percent reliability by replacing missiles he knows to have failed with missiles in his reserve. The multiple warheads of a MIRVed system, however, do not achieve uniform reliability and accuracy, both of which can degrade after the first warhead is released—even though the first warhead is usually the one for which reliability and accuracy are quoted. The influence of each of these effects and their incumbent uncertainties is small for the nominal threat parameters.

Much has been written recently about fratricide, the final component of the survivability calculation, but little has been done to parameterize it. Fratricide can occur when a warhead enters the area around a previous nuclear explosion; the nuclear effects and debris from the first explosion can deflect, damage, or even destroy warheads which approach the area in which it detonated. This report introduces two models of fratricide. The first corresponds to that used by Steinbruner and Garwin in their well-known article in *International Security.* The other, an estimate by the present author, attempts to capture the more conventional view of fratricide. Both of these models are very uncertain, given how little really is known about fratricide.

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[7]One could argue that availability might also be included, depending upon whether or not Soviet targeting replaces those missiles that are not available at any given time.

[8]Tests might also not be representative of actual attack launches unless they are fired from operational silos using missiles that have received no more than normal maintenance. See Arthur D. Hadley, "Our Ever-Ready Strategic Forces," *Washington Star,* July 1, 1979, p. B-1.

ASSESSING POTENTIAL BASING OPTIONS

Although several new basing options have been suggested for the U.S. ICBM force, two of those considered most seriously have been shelter and trench basing. Both are designed to force the Soviets to target many aimpoints in order to destroy a single missile, and are therefore called multiple protective shelter (MPS) systems. Because they provide as many as 20 to 30 aimpoints for a single missile, and because 200 to 300 missiles would probably be deployed, MPS systems would compel the Soviets to use a substantial fraction of their mid-1980s force to destroy a high percentage of the U.S. ICBMs. Unfortunately, this kind of basing is so expensive that it will not be chosen unless it proves demonstrably superior to current silo basing. Given the potential importance of this comparison, it was chosen for an application of the methodology developed in Secs. III and IV.

As an introduction to that assessment, the sensitivity of survivability to the parameter changes of each basing option was compared for some of the most important survival parameters. The survivability of trenches was found to be most sensitive to changes in hardness and warhead yield—two parameters for which shelter survivability shows very little sensitivity and silo survivability only a moderate amount. The survivability of all three basing modes is very sensitive to accuracy changes, though silo survivability shows the greatest sensitivity and trench survivability the least. Finally, both shelter and trench survivability are much more susceptible to changes in reliability than is silo survivability. The survivability of these three basing modes is also sensitive to another potential change not introduced in the basic silo methodology: a change in the warhead configuration of Soviet missiles. In such a change, the Soviets could increase the number of warheads their missiles carry, at the cost of some sacrifice in the yield per warhead and in the total yield carried by a single missile. If the Soviets are free to change warhead configuration, they could dramatically affect the survivability of shelters, and also improve, somewhat, their performance against both trenches and silos, though these Soviet gains could be moderated somewhat by the ten-warhead-per-ICBM constraint in the SALT II agreement. The ability to change warhead configuration can also change the sensitivity of survivability to changes in other parameters. For example, shelter survivability could become far more sensitive to changes in CEP, though accuracy and reliability degradations for warheads released after the first could decrease this sensitivity somewhat.

In assessing the results of a Soviet attack against these basing modes, three other factors become important. First, the Soviet attack could be larger or smaller than postulated. Second, the United States

could deploy more or fewer shelters (aimpoints) than postulated. Third, the U.S. deception scheme could partially fail, leaving many shelters (aimpoints) clearly recognized as not containing a missile. Obviously, the latter two factors really do not influence the silo basing. Still, the pertinent factors can be combined into a single "attack multiplier" that can either increase or decrease the nominal Soviet threat. Because MPS systems depend mainly on not being targeted in order to survive, an attack multiplier of as little as 1.5 to 2 can "saturate" them to the extent that they provide little added survivability (compared with silos) for the ICBM force.

Figures 53 and 54 show an exemplary comparison of the three basing options. For the specific assumptions used herein, MPS systems are more survivable than silos, though by less than one would expect in some cases. That is especially true for the shelter basing mode, the advantages of which may be largely overcome by a change in the Soviet warhead configuration. Trenches may be significantly more survivable, though they are also potentially more susceptible to large degradations in their deception, and the fratricide model used for trenches is sufficiently questionable to make the actual level of survivability quite uncertain. All three basing modes are subject to significant uncertainties in their survivability, however—uncertainties that would be difficult to resolve, and which therefore preclude the Soviets from gaining high confidence in anything like a reasonable level of ICBM destruction.

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CONTENTS

FIGURES

GLOSSARY AND SYMBOLS

A	Number of flight tests that failed (because of unreliability) out of a total of T
A_{vn}	Overpressure pulse duration correction for the VN
B_h	Systematic error in height of burst caused by the systematic bias (accuracy) error
Bias	Systematic bias error (the distance between the target and the mean point of impact)
CEP	Circular error probable (distance from mean point of impact within which 50 percent of many shots should fall)
$\overline{CEP}$	"Average" CEP from T flight tests
DF	Statistical "degrees of freedom" in a test program (which is one less than the total number of tests)
DIA	Defense Intelligence Agency
E	Fraction of a MAP system assumed to be "empty" of missiles
$E(\cdot)$	Expected value operator
EMT	Equivalent megatons (number of warheads times $Y^{2/3}$, Y in megatons)
F	Percentage of warheads surviving fratricide
h	Overpressure produced at the target (distance x from detonation)
h_o	Overpressure required to destroy a target (target hardness)
HOB	Height of burst of the warhead detonation
K	K-factor (a measure of overpressure pulse duration sensitivity)
kt	Kilotons (warhead yield, thousands of tons TNT equivalent)
l	Percent of unreliable warheads replaced by reprogramming
LB	Lower bound of uncertainty distribution
Ln	Natural logarithm
Log	Logarithm base 10
LR	Lethal radius of a warhead against a particular target type
LR_{50}	Lethal radius at which 50 percent of all targets would be destroyed
M	Attack multiplier (fraction of nominal attack delivered against defender's missiles)

m	Warheads (MIRVs) placed on each attacking missile
Mt	Megatons (warhead yield, millions of tons TNT equivalent)
$N(\mu,\sigma^2)$	Normal distribution, with mean μ and variance σ^2
n	Number of warheads attacking each silo or aimpoint
n mi	Nautical miles
p_{50}	Overpressure required to destroy a target with 50-percent probability (the basis of a VN)
PA	Probability a warhead arrives and detonates on target
PDT	Probability that at least one warhead will detonate on target
PK	Multiple-shot kill probability
PS	Probability of survival (PS = 1 − PK)
psi	Overpressure measure (in pounds per square inch)
R	Percent of planned MPS system that is actually built
r	Warhead reliability
r'	Net warhead reliability once augmented by reprogramming
r_d	Dependent warhead reliability
r_i	Independent warhead reliability
r_n	Nonreprogrammable warhead reliability
r_p	Reprogrammable warhead reliability
S	Attack size
s	Observed standard deviation
SSPK	Kill probability to a target of a single arriving, detonating warhead
SSPS	Survival probability of a target to a single arriving, detonating warhead (1-SSPK)
T	Number of tests made of a parameter's value
U	Number of successful test shots out of a total T
UB	Upper bound of uncertainty distribution
$var(\cdot)$	Variance operator
VN	Vulnerability number representation for target hardness
VN_o	VN before adjustment for sensitivity to overpressure pulse duration
WR	Weapon radius of a warhead against a particular target type
x	Ground distance from warhead detonation
x_o	Ground distance between detonation and location that receives overpressure h_o
Y	Warhead yield (total energy released by the warhead explosion, in TNT equivalents)
Z	Scaled distance (thousands of feet)
α	Cumulative probability of a particular statistical test
β	A function of the damage sigma (σ_d), used in SSPK

λ	Slope of log-log plot for overpressure versus ground range ($\lambda = \phi/\beta$)
σ	Standard deviation (square root of variance)
σ_C	Standard deviation of cross-range impact errors
σ_D	Standard deviation of downrange impact errors
σ_d	Damage sigma (of lognormal damage distribution)
σ_h	Standard deviation of height of burst variability
σ_{WR}	Standard deviation of weapon radius uncertainty
χ^2	Chi-square statistic

I. INTRODUCTION

Intercontinental Ballistic Missiles (ICBMs) are one of the three legs of the United States strategic forces triad. That triad is intended to give both flexibility and survivability to the U.S. strategic deterrent threat: "To preserve deterrence, U.S. forces must be designed so that, if necessary, they are able to absorb an attack—rather than depend on warning for their survival—and strike back after enemy weapons have actually detonated. The most efficient basis for such a second-strike capability is a mixed force of ICBMs, SLBMs, and bombers—known as the strategic Triad—which interact strongly to increase the survivability of each part."[1] Over the last several years, a number of reported developments in Soviet ICBMs have begun to raise strong questions about the survivability of U.S. ICBMs, which in turn raise questions about how to retain a viable triad. Although most authors are quick to point out that the Soviet threat is very uncertain, almost all quantitative analysis of ICBM survival ignores the uncertainties.[2] While that traditional approach nicely simplifies the calculations, it may mislead decisionmakers by obscuring the potential magnitude and implications of the uncertainty in survivability.

The purpose of this report is to develop a methodology for assessing the survivability of an ICBM force, given uncertainty. The methodology requires three specific types of changes from the traditional model of ICBM survivability. First, the assessment includes a variety of factors excluded from the traditional model. Second, the sensitivity of survivability to each factor is evaluated. Finally, the potential uncertainty in each factor is estimated, and the effect of this uncertainty on survivability is assessed.

The traditional model of ICBM survivability is presented in Sec. II. That model provides a simple set of formulas for estimating survivability. Once the model itself is developed, various threat data are used in it in order to establish a significant nominal threat. The problems with this model are then noted, and their potential impact is addressed. Section II also discusses the various types of uncertainties, and how each can affect estimates of survivability.

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[1]Donald H. Rumsfeld, *Annual Defense Department Report, FY 1978*, January 17, 1977, p. 19.

[2]A notable exception is *Counterforce Issues for the U.S. Strategic Nuclear Forces*, Congress of the United States, Congressional Budget Office, January 1978, which used the SNAPPER exchange model (originally designed by this author) to perform its analysis, as described on pp. 57-73 therein.

A more complete methodology for assessing ICBM survivability includes four dimensions. The first, single-shot kill probability (SSPK), is the subject of Sec. III. SSPK is the probability that an attacking warhead will destroy an ICBM in its silo if the warhead arrives and detonates in the vicinity of the target. Thus, SSPK is a function of target vulnerability, warhead destructiveness, and warhead accuracy. For the nominal threat developed in Sec. II, this section shows that SSPK can be very uncertain.

Section IV develops the other three dimensions of ICBM survivability: multiple-shot kill probability, warhead arrival, and fratricide. Each relates to the difficulty of getting warheads to the target, or to what happens when more than one warhead does arrive and detonate. Combining SSPK with all of these dimensions completes the methodology for assessing ICBM survivability. A series of appendixes, which provide technical details for this formulation, are contained in a companion report, R-2578-FF.

To show the potential policy relevance of this methodology, it is applied to the question of ICBM basing options in Sec. V. With the concern over ICBM survivability, numerous alternatives have been suggested to replace or augment the current silo basing. The two most popular of these options—shelters and trenches—are compared with silo basing for a fixed threat. The relative sensitivity of each to changes in that threat are also examined, and the overall impact of uncertainty on survivability of each option is assessed. The author concludes that this methodology provides a viable basis on which to make such comparisons, though specific policy choices are sensitive to, and thus must reflect, our best estimate of the threat the ICBMs face.

II. THE TRADITIONAL MODEL OF ICBM SURVIVABILITY

Most assessments of ICBM survivability are performed with a simple formulation, referred to herein as the traditional model. This section discusses the nature of and problems with the traditional model. It begins by presenting the formulation of this model. The model is then applied to exemplary threat data, showing the scenario and conditions required to pose a significant threat to survivability. The section then addresses the potential effect of uncertainty on survivability, and concludes by briefly assessing some of the problems with the traditional model.

FORMULATING THE TRADITIONAL MODEL

The traditional model of ICBM survivability begins by recognizing that the detonation of a nuclear weapon produces a variety of weapon effects that could destroy an ICBM in its silo. The effects of an exploding warhead will be lethal out to some distance, usually referred to as the lethal radius (LR). The lethal radius of a nuclear warhead is a function both of its destructive power and of the vulnerability of the target. In the traditional approach, the power of the warhead is measured by its yield (Y). The vulnerability of a target is measured by its hardness (h_o), which is the amount of air blast overpressure (in pounds per square inch above normal atmospheric pressure) that a target can survive.

The traditional model assumes that a nuclear warhead destroys an ICBM in its silo if the silo is within the lethal radius.[1] Thus, in most cases, the warhead is aimed directly at its silo target. During its flight, however, a variety of factors can cause a warhead to stray from the intended flight path and miss the target. The resulting distribution of possible warhead detonation points is referred to as the accuracy of the warhead. Accuracy is usually measured by the circular error probable (CEP) around the intended target, which is the distance within which half of the warheads would detonate. Assuming that the

[1]That is, if the target is within the lethal radius, it is completely destroyed; if the target is outside the lethal radius, it is completely undamaged. Thus a near miss does not make the target easier to destroy for subsequent warheads. This kind of damage function is generally referred to as a "cookie-cutter" because of its sharp, complete damage/no damage formulation.

warhead detonations are circular normally distributed around the silo target, the probability that the silo survives a single detonating warhead (the single-shot survival probability—SSPS) can be expressed as:

$$SSPS = 0.5^{\left(\frac{LR}{CEP}\right)^2}$$

Thus, if the lethal radius exactly equals the CEP, the SSPS is 50 percent because the warhead will detonate within the lethal radius half of the time.

If more than one warhead detonates at the same target, the effect of each is assumed to be "independent"[2] of the effects of all others. Once independence is assumed, the probability that the silo survives an attack by more than one warhead (the multiple-shot survival probability—PS) can be simply formulated as the product of the SSPS of each warhead, or for n identical warheads:

$$PS = SSPS^n$$

$$= 0.5^{n\left(\frac{LR}{CEP}\right)^2}$$

The above formulation for PS assumes that all n warheads arrive and detonate in the vicinity of the target. In reality, each warhead has less than a 100-percent probability that it will perform properly. The probability of proper performance, usually referred to as arrival probability (PA), can be taken into account in the PS formula in two ways. Some analysts simply deflate the number of identical warheads (n) used by the arrival probability ($n' = n \cdot PA$), retaining the basic format of the above equation for PS. However, most analysts recognize that the correct procedure involves accounting for the failure of warheads to "arrive." Thus, for a single warhead:

$$PS = 1 - PA + PA \cdot SSPS$$

where $(1 - PA)$ is the probability that the warhead does not "arrive," and $(PA \cdot SSPS)$ is the probability that the target survives if the

[2]The effects of warheads from the same missile are usually not independent because much of both inaccuracy and the failure to arrive on target is due to missile problems that develop before the warheads separate from the missile "bus," and thus from each other. Therefore, this condition usually requires that the warheads assigned to any given silo target come from different missiles. The "cookie-cutter" damage function also adds to independence by precluding a warhead from "softening" a target if it just misses killing the target.

warhead does arrive. For multiple, identical warheads, the formula becomes:

$$PS = \left(1 - PA + PA \cdot 0.5^{\left(\frac{LR}{CEP}\right)^2}\right)^n$$

The equations shown for PS above are basically the traditional formulations of ICBM survivability. These formulations are widely used today because of their simplicity, as will be demonstrated below.

SOME EXEMPLARY CALCULATIONS

Nearly all authorities agree that the Soviet Union will be able to pose a major threat to U.S. ICBM survivability in the mid- to late 1980s. For example, Secretary of Defense Harold Brown has presented a survivability best estimate of about five percent by then.[3] In most cases, these assessments of the Soviet threat are based upon a fairly simple attack scenario, and the attack results are evaluated by the traditional model. To provide a basis for comparison with the conventional wisdom on the Soviet threat, it is first necessary to establish the nature of the standard attack scenario, and then show the range of Soviet force capabilities (in terms of warhead yield, CEP, and arrival probability) for which a threat actually exists.

The standard scenario used in assessing U.S. ICBM survivability assumes a Soviet first strike against the ICBM force and some other targets. The attack against other targets will be ignored here because it is largely irrelevant to ICBM survivability.[4] The Soviets usually are considered to target two warheads at each silo.[5] The United States takes no direct response to protect its ICBMs from the attack, neither attempting to defend them with an antiballistic missile system nor launching them on warning of the attack, before the attack arrives. In almost all analyses, it is assumed that the hardness of the U.S. ICBM silos is 2000 psi, with a corresponding lethal radius of 0.2 nautical miles for a one-megaton ground burst.[6] Thus, the survivability of the

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[3]Harold Brown, *Department of Defense Annual Report, Fiscal Year 1980,* January 5, 1979, pp. 116-119.

[4]The possible exceptions to this statement involve attacks against capabilities that support the ICBM force, such as launch control centers, the power system, and support and maintenance bases. Because the precise impact of attacks on these facilities is hard to measure, it is usually ignored.

[5]Two warheads are used because arrival probabilities of modern systems are not high enough to cause really low survival probabilities with a single warhead attack, and because fratricide probably precludes the detonation of more than two warheads from the same attack wave at a single silo. Both of these problems are discussed in more detail below.

[6]Only a few analyses today use a U.S. Minuteman silo hardness of other than 2000

ICBM force in this scenario is a direct function of the performance of the attacking Soviet warheads, easily calculated using the formulas above. In particular, since the lethal radius is a function of yield to the one-third power, the PS for two attacking warheads can be expressed as:

$$PS = \left(1 - PA + PA \cdot 0.5^{\left(\frac{0.04 \cdot Y^{2/3}}{CEP^2}\right)}\right)^2$$

where Y is the warhead yield in megatons and CEP is expressed in nautical miles (n mi). Since the Soviets are striking first against undefended U.S. silos, the PA equals the reliability of their missile systems.

The public literature contains a variety of estimates of Soviet ICBM performance. For example, in a recent *Scientific American* article, Bernard Feld and Kosta Tsipis[7] suggest that Soviet yields are in the 400 kt to 750 kt range, that Soviet arrival probabilities would be in the 66-percent to 80-percent range, and that Soviet CEPs might range from 0.12 to 0.25 n mi. The CEP differences are partly explained by changing technology, with a CEP of 0.17 n mi given for today, and a CEP of 0.12 n mi suggested for the mid-1980s. Also, a Soviet CEP of 0.25 n mi was widely used around 1976-1977 just after the current Soviet ICBMs were initially deployed. Using these various estimates, Feld and Tsipis apply the traditional model, producing estimates of ICBM kill probability (the opposite of survivability) like those shown in Table 1.[8] As Feld and Tsipis state, these numbers indicate that, for past and present accuracies, the Soviets have had the ability to destroy some, but certainly not a major part, of the U.S. ICBM force.

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psi. Most of those analyses use 1000 psi (compare Clarence A. Robinson, Jr., "MX Deployment Urged for Parity," *Aviation Week and Space Technology*, December 5, 1977, p. 14, with John Steinbruner and Thomas Garwin, "Strategic Vulnerability: The Balance Between Prudence and Paranoia," *International Security*, Summer 1976, p. 146). The Titan II force has a hardness around 300 psi (Steinbruner and Garwin); since it is much smaller and more vulnerable than the Minuteman force, the survivability of the Titans is seldom explicitly calculated. For the lethal radii of different target hardnesses, see Samuel Glasstone and Philip J. Dolan (eds.), *The Effects of Nuclear Weapons*, U.S. Department of Defense and U.S. Department of Energy, 1977, pp. 110-115.

[7]"Land Based Intercontinental Ballistic Missiles," *Scientific American*, November 1979, pp. 51-61.

[8]Feld and Tsipis's numbers differ somewhat from those in Table 1, partly because they made some errors in their calculations. They show a 79-percent kill probability for 0.17-n mi-CEP, 750-kt, 80-percent reliable warheads when the number should really be 69 percent (as borne out by examining the kill probability they calculate for an attack by one such warhead). In general, though, the differences are only one percent when they do occur, and simply suggest a different round-off procedure or some such problem. (The present author used a computer program that constantly maintained six significant digits.)

By 1985, however, the threat is much more substantial, especially if Soviet accuracy, yield, and reliability are as good as they can be. Thus, while Feld and Tsipis's numbers show how much survivability can vary, the threat they reveal is lower than Harold Brown's best estimate (which Feld and Tsipis cite as well).

Table 1

FELD/TSIPIS ESTIMATES OF SILO KILL PROBABILITY

Yield (kt)	Reliability (%)	Silo Kill Probability (%), Two-Warhead Attack: About 1976; CEP = 0.25 n mi	About 1979; CEP = 0.17 n mi	About 1985; CEP = 0.12 n mi
750	80	43	69	87
750	66	37	59	78
400	80	31	55	77
400	66	26	47	67

High threat estimates like Brown's must attribute higher values to Soviet weapon system performance. Robinson's 1977 article in *Aviation Week and Space Technology* provided just such values.[9] In particular, by 1985, Robinson postulated a Soviet warhead yield of one megaton, a CEP of 0.1 n mi (roughly 610 feet), and an arrival probability of 90 percent. While only slightly better than the estimates for each parameter shown by Feld and Tsipis, Robinson calculated a kill probability (PK) of 96 percent for a two-warhead attack. Since this result is essentially the same as Brown's, the parameters suggested by Robinson will be used in the remainder of this report to parameterize a nominal mid-1980s Soviet attack that poses a serious threat to U.S. ICBM systems. For reference purposes, the traditional model gives an SSPK of 94 percent and a PK (for two independent warheads) of almost 98 percent for this nominal threat.[10]

UNCERTAINTY IN SURVIVABILITY

The wide ranges of values shown for each parameter above are characteristic of the data available. Such large uncertainties in basic

[9]Robinson, "MX Deployment."

[10]In his calculations, Robinson apparently used a model similar to the traditional model but with a circular normal damage function, like that used in the Rand damage probability computer. See D. C. Kephart, *Damage Probability Computer for Point Targets with P and Q Vulnerability Numbers*, The Rand Corporation, R-1380-1-PR, February 1977.

parameters in turn make ICBM survivability very uncertain. To understand the potential range of survivability estimates, it is important to parameterize each of the component uncertainties, and show how they can affect overall survivability.

"Uncertainty" in the parameters and models of ICBM survivability has three components: random variations, mean value uncertainty, and parameter/model unknowns. Random variations are fluctuations around the mean or average performance that can be expected because of the nature of a system. For example, the yield of any given warhead may vary from the nominal value for that type of warhead because of minor differences in the quality and/or quantity of materials therein or how they are assembled. Random variations are also observed when a mean value has no operational meaning; for example, warheads either arrive or they do not, and the arrival probability simply attempts to measure an average of this phenomenon. Random variations affect survivability most strongly when only a small number of events are involved, making any variation from mean performance potentially significant. For the larger attack sizes characteristic of attacks on an entire ICBM force, though, the effect of variations is much less. If, for example, an attack with a 5-percent PS is launched at only 10 ICBMs, we know that it will not kill exactly 9.5 (since you cannot kill half an ICBM); the number will more likely be either 9 or 10. In such an attack, simply the random variations around the PS would be expected to have a 7-percent standard deviation; but for an attack against 1000 ICBMs, this standard deviation would drop to 0.7 percent, a relatively trivial amount.[11] If the variations are not symmetric in their effects,[12] however, they can change the mean value of survivability from that calculated using the mean values of the parameters, as will be shown below. Still, these changes tend to be rather small (a few percent at most), and thus of relatively minor concern in estimating survivability.

Uncertainty in the mean values of parameters, as shown above, can have a much larger effect on survivability. Examining just this kind of uncertainty in yield, CEP, and reliability, Harold Brown concludes that his 5-percent survivability estimate really could be as low

[11]Because this kind of random variation has little impact on the estimate of survivability and yet is time-consuming to assess on top of the other uncertainties, it will be ignored throughout the rest of this report, even when uncertainties are calculated. Thus, estimates of survivability uncertainty herein will tend to slightly underestimate the actual uncertainty. For further information on random variations, see App. A.

[12]For example, a 10-percent improvement in accuracy may decrease PS more than a 10-percent loss in accuracy would increase PS. In such a case, averaging the results across the possible variations around the nominal accuracy would tend to produce a decrease in the average PS from that calculated using only the "best estimate" parameters.

as 1 to 2 percent, and as high as 15 to 20 percent.[13] The difficulty in estimating the mean value of a parameter involves three points. First, so few tests are conducted from which to estimate these values that it is statistically impossible to reject a large range of possible values for the mean. Second, some procedures for measuring test results are less than perfect. For example, it is easy to tell whether a warhead arrives near a target during a test, but it may be difficult to determine whether its fuse would have worked.[14] Third, for parameters of Soviet systems, we either do not have directly observed results of their tests, or must rely on results recorded by scientific intelligence systems, which tend to be less accurate than the primary techniques the Soviets use for measurement. To the extent that these latter two problems can be solved, increasing the number of tests performed can help to resolve the uncertainty, though an unreasonably large number of tests may be required before some mean values can be estimated with adequate precision.

Unfortunately (or fortunately), a number of parameters and relationships in survivability either cannot be estimated or can be estimated only roughly. For example, because the Soviets have never fired an ICBM over the North Pole, they cannot know with any certainty the potential effect of gravitational or other anomalies on the path their warheads would follow in attacking U.S. silos. Similarly, because we (and probably the Soviets, too) have never tried a near-simultaneous detonation of two warheads over the same target, we cannot be sure of their interactions. Though we can develop theoretical models to estimate these effects, and though we can test some weapon components, our theoretical estimates tend not to be accurate enough to give us real confidence in estimating things we cannot directly measure.[15] Consequently, these aspects of survivability will tend to have the greatest uncertainty connected with them, and it will be almost impossible to resolve that uncertainty.

The primary aim of this report is to examine the uncertainties in the mean values of parameters and show how they apply to ICBM survivability. This report also discusses some of the aspects of the other two types of uncertainty, as well. Since the traditional model does not provide an adequate framework in which to assess those uncertainties, Secs. III and IV develop a methodology for handling them.

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[13]Brown, 1979.

[14]Of all parameters, warhead yield may be the most difficult to measure physically, since the amount of energy released in a large area is not easily measured.

[15]See the discussion of systematic bias in Robert G. Kaiser and Walter Pincus, "Shall We Attack America?" *Washington Post,* August 12, 1979, p. B-1.

PROBLEMS WITH THE TRADITIONAL MODEL

The traditional model fails to portray ICBM survivability accurately because it is beset by a number of problems. As noted above, it completely ignores the substantial amount of uncertainty and variability in almost all aspects of survivability. Several problems also result from the model's simplifying assumptions. Further, a variety of parameters that affect survivability are ignored by the model because they are difficult to model or assess. These latter two types of shortcomings are particularly notable in five areas.

To begin with, the effective hardness of a given target is partially a function of the attacking warhead's yield. That is, higher values of warhead yield increase the duration of the overpressure pulse that hits the target; in turn, longer pulse duration can "soften" the target, decreasing its effective hardness. Unfortunately, the effect of pulse duration varies across target types. Therefore, a new system of measuring target vulnerability has been developed that measures both target hardness and its sensitivity to pulse duration. This system, known as the vulnerability number system, approximates the impact of pulse duration in an analytic form, though evidence is still lacking on how accurate this approximation is. Pulse duration can have a fairly significant effect on ICBM survivability.

The second complicating factor is the nature of the damage function. For a variety of reasons, primarily associated with random variations in target and weapon parameters, silo damage cannot be adequately estimated by a cookie-cutter function (complete destruction within the lethal radius, zero damage without). Rather, the probability of damage falls below 100 percent well within the "lethal radius," and decreases to zero well outside the "lethal radius." A lognormal damage function is commonly used today to capture this kind of variation in target damage, with a "damage sigma" measuring the variance of the damage density function (and thus being roughly correlated with its slope). Use of the lognormal damage function can increase the cookie-cutter SSPS by up to about 2.2 percent for the same basic parameters, a small but possibly significant difference.[16]

The third complicating factor is the nature of warhead accuracy (or, rather, inaccuracy). Though ideal warheads might fall in a simple, circular normal pattern around the target, this kind of pattern[17]

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[16]If survivability is only about 5 percent to begin with, a 2-percent increase (to 7 percent) may be fairly significant in a relative sense.

[17]Actually, warhead impacts may not be circular normal, but may fall in elliptical or other more complex patterns. Variations from the circular normal distribution are extremely difficult to model, are normally not very significant in effect, and are therefore normally ignored. See App. C for an assessment of these problems.

usually forms around a "mean point of impact" at some distance from the target. The distance between the target and the mean point of impact is referred to as systematic bias.[18] Thus, systematic bias measures true inaccuracy whereas the CEP measures the dispersion of potential impact points. The existence of systematic bias invalidates the simple formula for SSPS shown above, and makes any simple, analytic assessment of SSPS impossible. However, approximations have been developed that make it possible to calculate SSPS while accounting for systematic bias. Depending upon its magnitude, systematic bias can significantly increase SSPS, as will be shown below.

The fourth complicating factor is the proper representation of multiple warhead attacks, including warhead arrival. For a variety of reasons, the effects of multiple warheads are not independent, and therefore some procedure is required to account for the dependencies. In general, the dependencies do not have a powerful effect on survivability, though in specific cases they can be significant.

The fifth complicating factor is called fratricide, in which an arriving warhead is destroyed by the debris or nuclear effects coming from a previous nuclear detonation in the same area. Such warheads are as completely lost from the attack as if they had never arrived on target. There is no consensus within the community regarding the potential magnitude of this effect; some attempts to parameterize it are made below.

Other factors, most of them less significant, also might affect the simple formulation of PS. Among them are the choice of warhead height of burst, the interaction between accuracy and height-of-burst errors, other nuclear effects (especially ground shock), and attack timing. In some cases the effect of these factors can be easily estimated, while in other cases (such as ground shock) no such estimate is widely accepted. Procedures for addressing essentially all of the above problems are presented in Secs. III and IV and in App. C.

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[18]Systematic bias is referred to as an average or "gross" miss. It should also be noted that warheads falling a distance more than three times the CEP from the target (or mean point of impact) are assumed to have "failed," and thus are excluded from the test samples used to calculate CEP and bias. This exclusion improves the estimated CEP while causing the reliability estimate to be somewhat lower. These failures are sometimes referred to as a complete or "gross" miss, bearing no relationship to the "gross" miss of systematic bias.

III. SINGLE-SHOT KILL PROBABILITY

Single-shot kill probability (SSPK, the complement of SSPS) is one of the four dimensions of silo survivability. There are a variety of formulations of SSPK,[1] including the traditional model shown in the previous section. This section develops a procedure for examining SSPK that includes the uncertainties ignored by the traditional model and overcomes many of its other problems. The section begins by examining the three components of SSPK: target vulnerability, warhead destructiveness, and the accuracy with which warheads can be delivered. The uncertainties in each of these factors are then assessed. Finally, the effect of the combined uncertainties on SSPK is shown.

TARGET VULNERABILITY

A nuclear explosion produces several types of destructive effects, including blast effects (overpressure and dynamic pressure), prompt radiation, thermal radiation, cratering, ground shock, electromagnetic pulse (EMP), and fallout. For most silo types, and for the megaton range yield of Soviet warheads, radiation effects (including EMP) are probably not a major source of damage to a missile protected in a silo.[2] Of the other effects, cratering will cause the most damage if the detonating warhead lands close enough to the silo, but cratering will not extend as far as the lethal blast effects against present silos, and thus is not the determining factor of a warhead's lethal radius. Either blast effects or ground shock could be the determining factor for varying silo designs;[3] however, because it is easiest to base the formulation of SSPK on blast effects, ground shock is usually either

[1]Some examples are given in Lynn Etheridge Davis and Warner R. Schilling, "All You Ever Wanted to Know About MIRV and ICBM Calculations But Were Not Cleared to Ask," *Journal of Conflict Resolution*, Vol. 17, No. 2, June 1973, pp. 210-216.

[2]Kosta Tsipis, *Nuclear Explosion Effects on Missile Silos*, Center for International Studies, Massachusetts Institute of Technology, February 1978, p. 38. According to Tsipis, radiation effects can destroy the electronics involved in missile support, launch, or guidance, but not the missile or silo itself, and generally will not affect the electronics of an ICBM in its silo. Repair of the electronics could be difficult, preventing missile launch until repairs are completed. Ibid., pp. 11-19. Also, fallout could prevent repair crews from working on damaged missiles even though it would not in and of itself cause any damage to a missile.

[3]Ibid., pp. 19-52.

ignored or "factored into" the assumed blast vulnerability of a silo (by choosing a lethal overpressure with the same lethal radius as the ground shock).

Blast vulnerability of silos or other targets is usually represented in one of two ways. The traditional model uses the overpressure required to destroy a silo,[4] with U.S. silos normally expected to resist overpressures up to 2000 psi. In contrast, a more recent and now widely accepted procedure represents silo hardness as a "vulnerability number" of the form "VNTK." In this form, "VN" is a logarithmic transformation of the overpressure[5] resistance (or hardness) of a target, "T" is an indicator of the type of blast sensitivity (a "P" for overpressure, a "Q" for dynamic pressure), and "K" is a measure of the target's sensitivity to the duration of the blast pulse. Thus, if U.S. silos were of moderate sensitivity to blast pulse duration, they could be represented by a vulnerability number of 43P4.[6] Vulnerability numbers use a cumulative lognormal distribution to measure the damage done at any given distance from the warhead detonation. This distribution is parameterized by a weapon radius and a "damage sigma," σ_d. The σ_d roughly correlates with the slope of the damage function; for an overpressure-sensitive target, σ_d normally equals 0.2.[7]

Of these two representations, the vulnerability number has several advantages. One of the most important is that it gives a convenient way to account for the effects of pulse duration, which are normally not taken into account in the pressure representation (though the precision of this representation is still questioned by some in the community). The VN system also provides a variance (σ_d^2) that primarily reflects variations in target hardness due to structural dif-

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[4]See description in Glasstone and Dolan, pp. 80-126.

[5]That is, for a target most sensitive to overpressure:

$$VN = 12.63 \cdot \text{Log}\,(p_{50}) - 0.63$$

where p_{50} is the overpressure required to obtain a 50-percent kill probability against the given target type. Thus, if $p_{50} = 10$ psi, then VN = 12. Vulnerability numbers are described in detail in App. B.

[6]To go from overpressure to the vulnerability number, an adjustment for the pulse duration must be made to the equation in the previous footnote (which yields a VN of 41.06 for $p_{50} = 2000$ psi). For a moderate K value of 4 and for one-megaton-range weapons, this "VN" must be increased by two, to 43, to account for the potential of pulse duration. Note also that only integer values are used for both "VN" and "K" by convention. See App. B for details.

[7]For more information on this subject, see App. B, which compares calculations of these two types. Also, see DIA, *Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons*, DI-550-27-74, November 1, 1974, with Change 1 (August 1, 1976). Note that σ_d does not equal the slope of the damage function, but rather correlates closely with it.

ferences of similar targets.[8] While the pressure system could also use such a variance, it would have to use mathematics inherent to the VN system in order to do so. Thus, even though the pressure formulation is somewhat easier to understand because of its physical meaning, the vulnerability number system will be used herein.

The basic Soviet countersilo attack data introduced in Sec. II[9] are used in Figs. 1, 2, and 3 as a basis for demonstrating the sensitivity of the nominal SSPK to the vulnerability number representation of missile vulnerability. Each of these figures employs the nominal threat data, except that one item (that shown on the x-axis) is allowed to vary around the nominal value (which is marked by an arrow on the x-axis). The nominal SSPK is roughly 93 percent, compared to the value of 94 percent generated by the traditional model for this same basic threat.[10] Figure 1 shows that the SSPK decreases fairly quickly as the VN increases, the decrease being most rapid for a fixed (1000-foot) height of burst. This latter point is true because, even for the same warhead yield, the optimum height of burst[11] is lower for harder targets (larger VNs). That is, the optimum height for one hardness will be too high to effectively damage very much harder targets (a relationship described more fully in Fig. 5).

SSPK is much less sensitive to changes in the K-factor and in the damage sigma. As the K-factor increases, Fig. 2 shows that the expected SSPK also increases slightly. That is because a larger K-factor means a larger overpressure pulse duration sensitivity, making targets "softer" to large-yield warheads (above 20 kt) and "harder" to small-yield warheads (below 20 kt). In other words, the magnitude of the slope of this curve is a function of the yield used, and would decrease as warheads with yields smaller than one megaton were used (with the same initial SSPK for $K = 4$) until it actually started running in the other direction below 20 kt. As the damage sigma (σ_d) increases,

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[8]Target-hardness variation is a target-to-target variation, as opposed to a weapon-to-weapon variation. The distinction is discussed in App. A.

[9]The basic data employed are a 1000-kt warhead yield, 600-foot CEP, and a 2000-psi overpressure hardness converted to a 43P4 vulnerability number. To illustrate the methodology for coping with two other sources of uncertainty, each warhead is airburst rather than groundburst, and a 200-foot systematic bias is assumed.

[10]The traditional model's SSPK of 94 percent is based on a groundburst weapon. A comparable groundburst in the vulnerability number system would yield an SSPK of 90 percent. The difference is due to the use of a damage sigma and a lower weapon radius (a probable error in this formulation), as detailed in App. B.

[11]Each warhead-yield/target-hardness combination has associated with it a fixed height of burst above the ground at which more damage can be done to the target than at any other height of burst. This height is called the optimum height of burst. It is normally greater than zero (above the ground) because airbursts produce a "mach stem" effect of incident and reflected overpressure that is greater than the simple incident overpressure would be. See Glasstone and Dolan, pp. 111-115.

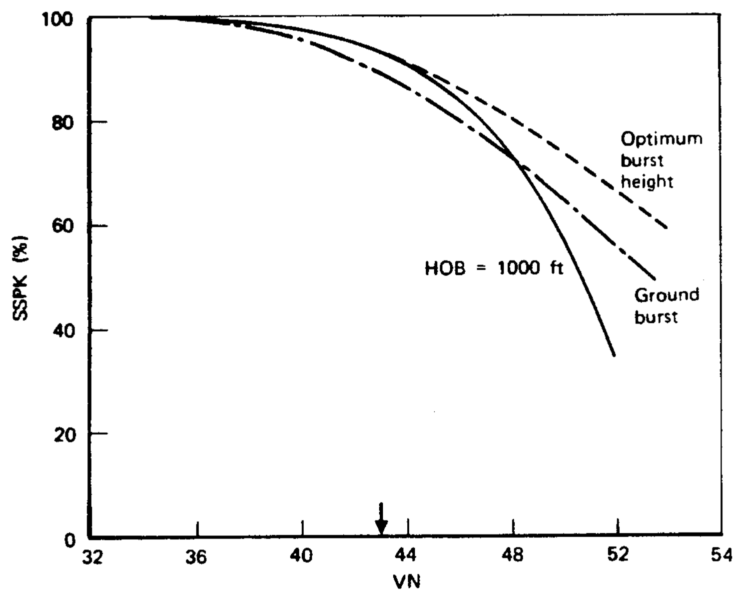

Fig. 1—Relationship between VN and SSPK

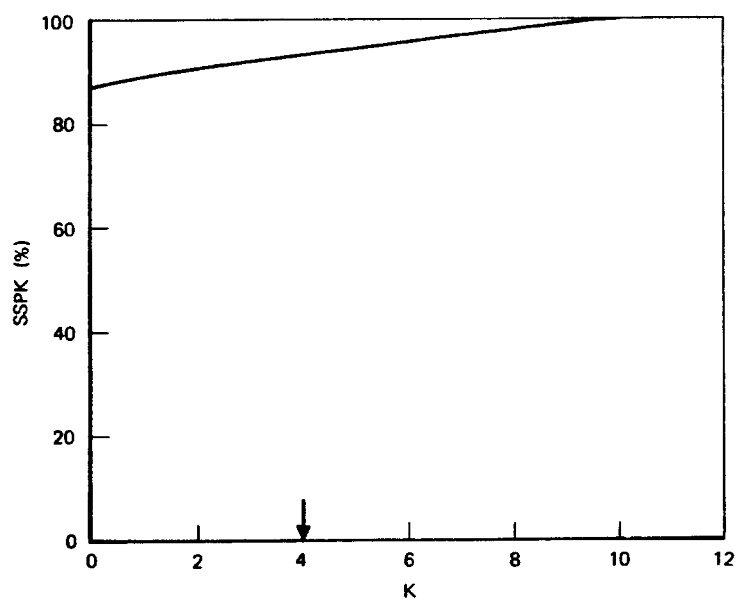

Fig. 2—Relationship between K-factor and SSPK

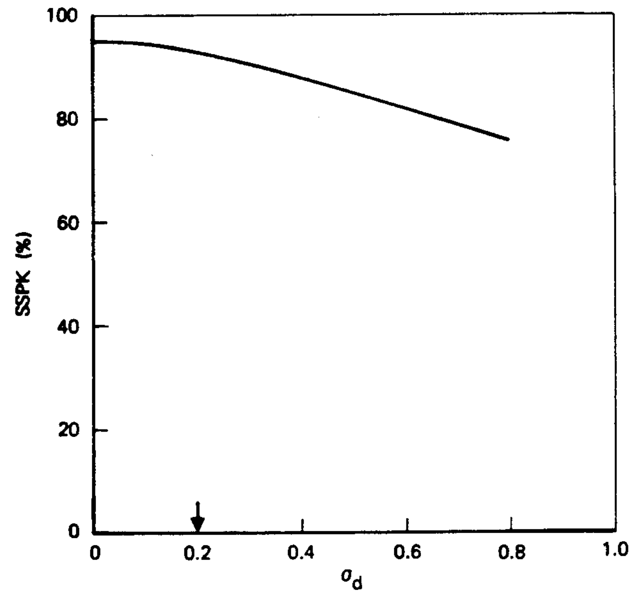

Fig. 3—Relationship between σ_d and SSPK

Fig. 3 shows that SSPK slightly decreases. Thus for target types with a high variance in vulnerability (high σ_d) the expected SSPK is somewhat less because higher proportions of individually very hard targets are included in the target type mix. A "cookie-cutter" damage function ($\sigma_d = 0$, as used in the traditional model) produces the highest estimate of SSPK, comparable in value to the traditional model SSPK estimate.[12]

WARHEAD DESTRUCTIVENESS

In the traditional model, warhead destructiveness is represented only by the yield of the warhead. However, the destructiveness of a nuclear weapon is actually a function of (1) its yield (that is, the total amount of energy produced by its explosion), (2) its type (which tells how that energy is distributed among the various types of nuclear effects), (3) its fission yield (which determines the amount of radioac-

[12]Appendix C discusses in some detail the damage sigma and how it relates to SSPK.

tive fission products contributing to fallout), and (4) its height of burst. Because fallout will be ignored here, the fission yield can also be ignored. Further, for the indicated focus on blast effects only, most strategic nuclear weapon types cause similar results at the same yield, and thus weapon type can also be ignored.[13] However, a fair amount of uncertainty is associated with the lethal or "weapon radius"[14] for a given warhead yield and height of burst.[15] Thus, warhead destructiveness herein includes both the height of burst and the true value of the weapon radius, as well as the warhead yield.

Figures 4, 5, and 6 illustrate the relationships between the warhead destructiveness parameters and SSPK, based upon the nominal threat data. Figure 4 shows three curves: one for an optimum airburst, one for a fixed height of burst of 1000 feet, and one for a groundburst. Above one megaton, the SSPK increases slowly because it is already very close to 100 percent. Below one megaton, SSPK decreases slowly at first, and then quite rapidly below about 500 kt, especially for the fixed 1000-foot height of burst. The reason for this, and for the similar pattern for the fixed burst height line in Fig. 1, can be understood from Fig. 5. Here it is shown that in moving from a groundburst to optimum burst height,[16] about 4 percent is gained in SSPK. Above the optimum burst height, however, the SSPK begins to fall quickly, until, at not too much higher a burst point, the SSPK would eventually reach zero.[17] For a warhead smaller than one megaton, the optimum height of burst

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[13]This would apparently not be true for enhanced radiation weapons, which shift at least some of the energy of nuclear weapons from blast to prompt radiation effects, changing the relationship between yield and blast effects, though such weapons are usually much smaller in yield than the strategic warheads that will be considered herein.

[14]The "weapon radius" is the "lethal radius" of the vulnerability number system. It is compared with the lethal radius of the traditional model in App. B.

[15]To understand this uncertainty, one need only examine the many formulations that have appeared over the years of overpressure versus ground distance from the actual ground zero. The changes that have occurred may be partially due to improved instrumentation, though they clearly reflect the real uncertainty of the "physics" here. Glasstone and Dolan, in their preface, state: "We should emphasize, as has been done in the earlier editions, that numerical values given in this book are not—and cannot be—exact. They must inevitably include a substantial margin of error. Apart from the difficulties in making measurements of weapons effects, the results are often dependent upon circumstances which could not be predicted in the event of a nuclear attack. Furthermore, two weapons of different design may have the same explosive energy yield, but the effects could be markedly different." Some of these difficulties include: terrain effects, meteorological conditions, differing altitudes and temperature, and surface effects. See Glasstone, pp. 92-96.

[16]The optimum burst height is the height at which the highest SSPK occurs. In Fig. 5 it is about 1000 feet (100 scaled feet), with an SSPK of 93 percent.

[17]This curve is stopped before SSPK reaches zero because the vulnerability number methodology is not very accurate in this region. This information derives from an interview with Dr. Paul Castleberry of DIA's Physical Vulnerability Branch, December 1976.

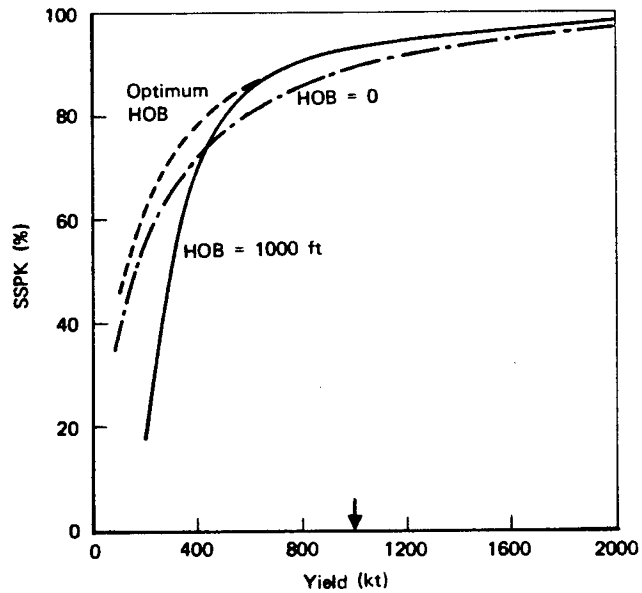

Fig. 4—Relationship between yield and SSPK

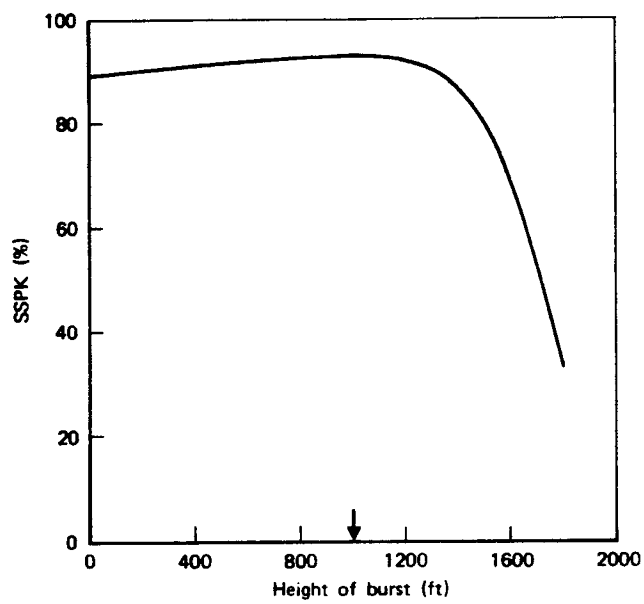

Fig. 5—Relationship between height of burst and SSPK

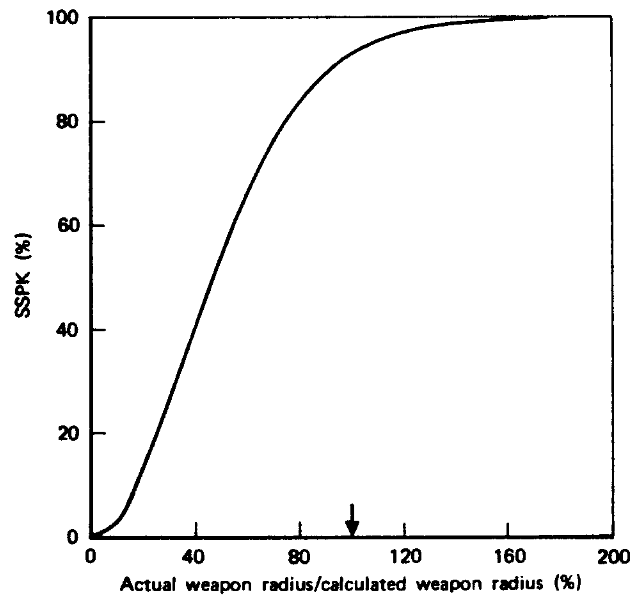

Fig. 6—Relationship between actual weapon radius and SSPK

is proportionately (to yield to the one-third power) lower, eventually causing a burst at 1000 feet to have an SSPK even lower than that of a groundburst because it is detonated too high. The same kind of change occurs with an increase in the vulnerability number, which also lowers the optimum burst height (though not quite proportionately). Finally, Fig. 6 shows how variations in the actual weapon radius affect SSPK, with a very sharp decrease below the calculated radius and a fairly sharp increase above it.

WARHEAD ACCURACY

Once the lethal radius or weapon radius of a warhead/target combination is known, the SSPK is determined by where the warhead lands with respect to the silo target. Warheads are usually aimed exactly at the target, but various inaccuracies in the flight path and anomalies in the warhead's environment can cause the warhead to miss the target by some distance. Some of these inaccuracies being random, they produce a pattern of impact points over many shots. In almost all SSPK formulations, the impact points are assumed to be part of a circular normal distribution around a mean point of impact,

parameterized by the CEP.[18] As Sec. II noted, however, other inaccuracies in impact may be present in every shot using the same guidance system and basic trajectory, leading to a systematic bias, which is a separation between the aimpoint and the mean point of impact of a series of flight tests.[19]

Figures 7 and 8 show the relationships between these two accuracy parameters and SSPK. In Fig. 7 it can be seen that even with a 200-foot systematic bias, CEPs of 300 feet or less produce essentially a 100-percent SSPK. Above 300 feet, the SSPK falls rapidly, eventually becoming asymptotic to zero. The curve for bias is similar in Fig. 8, though even with a zero bias the nominal threat produces only a 94-percent SSPK. The bias curve is somewhat steeper than the CEP curve, however, as a substantial bias quickly lowers SSPK when the CEP is relatively small, as in this example.

UNCERTAINTY DISTRIBUTIONS FOR THE MEAN VALUES OF THE SSPK PARAMETERS

In Figs. 1 to 8, SSPK was determined on the basis of the nominal values for each parameter. Uncertainty in the actual mean value of these parameters would cause SSPK to vary as shown by the curves in those figures.[20] To measure the effects of these uncertainties, we must first determine the uncertainty distribution associated with each parameter. These uncertainty distributions can be estimated from theoretical formulations of the uncertainty, and from the test data for each parameter. Even with this information, however, it is doubtful that a single, precise distribution could be chosen because of the similarities of many distributions. Therefore, while recognizing that choosing the "right" distribution is an important problem, this report makes the simplifying assumption that the uncertainties in most of

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[18]The CEP can be shown to be 1.1774 times the standard deviation of the appropriate normal distribution. See DIA, p. 18. Deviations from these simplified assumptions are treated in App. C.

[19]This problem is discussed in some detail in James L. Foster, "Essential Equivalence: What Is It and How Should It Be Measured?" in *Equivalence, Sufficiency, and the International Balance*, Proceedings of the National Security Affairs Conference, Office of the Assistant Secretary of Defense (International Security Affairs) and the National Defense University, August 1978, pp. 35-38.

[20]Actually, the so-called "mean value" of CEP is an estimate of the dispersion of warhead impact points, calculated from the standard deviation of impacts in the downrange and cross-range directions, as shown in App. C. To simplify terminology, however, this estimate of CEP will be referred to as a "mean value."

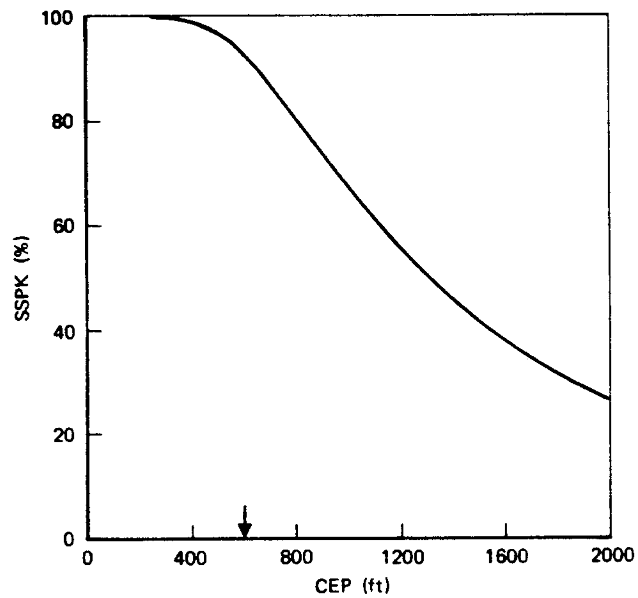

Fig. 7—Relationship between accuracy and SSPK for bias = 200 ft

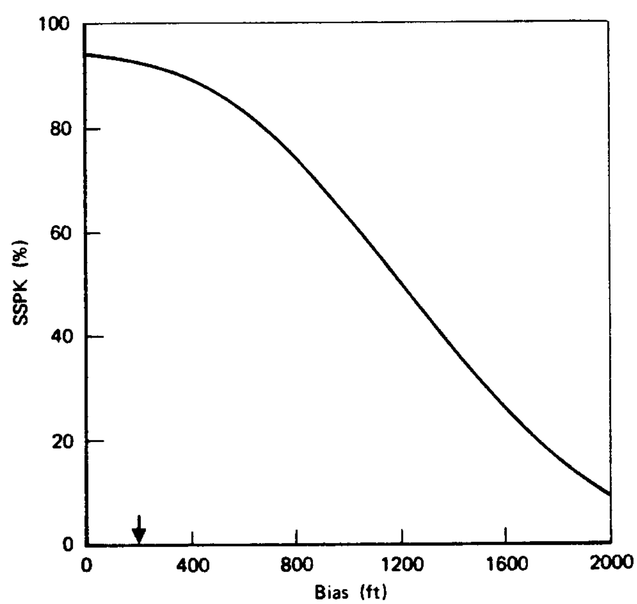

Fig. 8—Relationship between bias and SSPK for CEP = 600 ft

these parameters are normally distributed around the nominal parameter values.

As an example, the possible uncertainty in the mean value of warhead yield is displayed in Fig. 9 (the solid line) as being normally distributed. The distribution is centered at the nominal value of one megaton, and the standard deviation (σ) was *arbitrarily* chosen to be 10 percent of that value, or 100 kt. Figure 10 shows the cumulative probability distribution for this mean and standard deviation, indicating that a 95-percent confidence interval for the expected yield in this case would run from about 800 kt to 1200 kt. If, then, this mean and standard deviation had been exactly determined (from design specifications or whatever), a 95-percent confidence interval for SSPK, given this uncertainty *only*, would be obtained by calculating the SSPK values corresponding to this range of yields from Fig. 4. Thus, SSPK would range from about 91 percent to 95 percent.

Most cf the information that we have about yield or any other parameter comes from tests designed to determine the parameter's

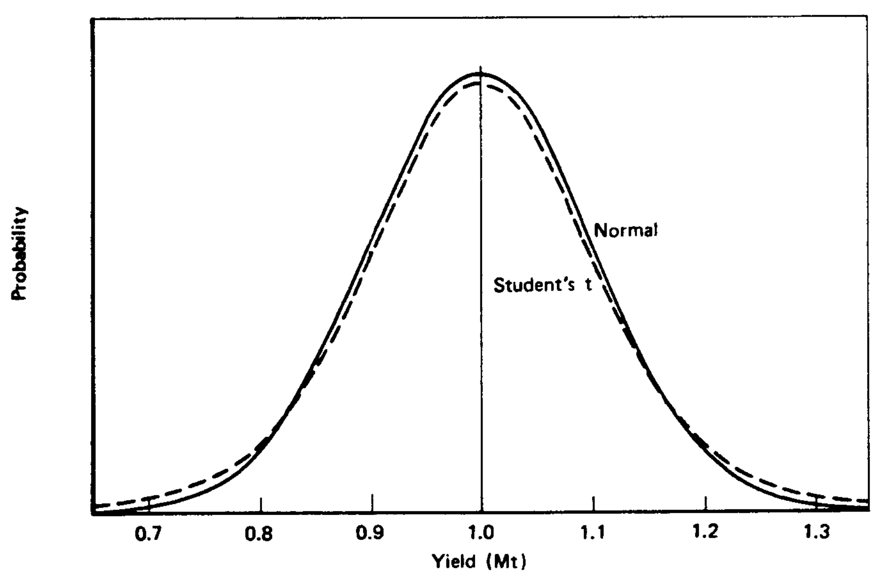

Fig. 9—Comparison or normal and Student's t distribution for uncertainty in yield, σ = s = 10% of expected yield

value.[21] These tests provide the data for calculating an average parameter value and a standard deviation around that average. However, because these statistics are based upon a finite number of tests, they should properly be associated with a Student's t distribution instead of a normal distribution. The Student's t distribution is designed for use with data that come from a normal distribution, but for which only an observed average and standard deviation(s) rather than the actual mean and standard deviation (σ) are known. A Student's t distribution for an average yield of one megaton, a standard deviation of 100 kt, and 10 tests is also given in Fig. 9 (the dashed line), and its cumulative distribution is given in Fig. 10. As can be seen, the tails of the Student's t distribution are somewhat higher than the normal distribution tails; this difference is due to the uncertainty added by having a sample average and standard deviation instead of the actual mean and standard deviation.[22] That difference decreases as the number of tests increases, though it would be higher if fewer tests were run. For the purposes of this section, it will be assumed initially that ten tests are run on all of the missile vulnerability and warhead destructiveness parameters.[23] That assumption leads to wider confidence intervals, with a 95-percent confidence interval of plus or minus 2.2 times the calculated standard deviation, as compared with 1.96 times the standard deviation for the 95-percent confidence interval of a normal distribution (if the same standard deviation is used).

Several of the parameters that have been discussed above are properly defined only over a fairly narrow range of values. For example, the K-factor must be greater than or equal to 0 and less than 10 (it is also normally constrained to be an integer value), and the damage sigma must be greater than or equal to 0 and less than about 0.7.[24] Also, most of the other parameters must be greater than or equal to 0 (these being yield, weapon radius, and—for our purposes—height of burst). Since those parameters are not strictly continuous, their uncertainty distributions must be truncated at these boundary values. That point

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[21]In some cases, the values for a new system may be projected from the test data of an old system by comparing the designs of the two. This approximation, however, adds its own uncertainty, and is still based on test data.

[22]This statistical point is discussed in more detail in almost any basic text on statistics.

[23]Ten may even be too high, as a smaller number of warhead-yield tests have apparently been run by the Soviets on any given warhead design. See Michael L. Squires, *Counterforce Effectiveness: A Comparison of the Tsipis "K" Measure and a Computer Simulation*, Center for Naval Analyses, Professional Paper 149, March 1976, pp. 8-10.

[24]Normally, the damage sigma ranges from 0.1 to 0.5, though a damage sigma of 0 is the "cookie-cutter," and values somewhat greater than 0.5 are not beyond possibility. See DIA, pp. 31, 79-81.

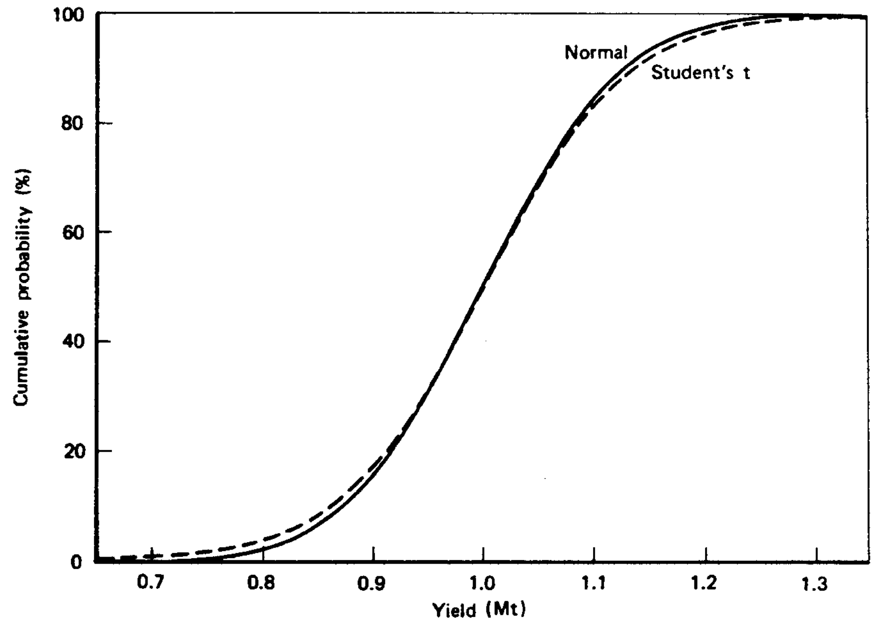

Fig. 10—Comparison of cumulative normal and Student's t distribution for uncertainty in yield, σ = s = 10% of expected yield

is illustrated for the K-factor in Fig. 11, where a standard deviation of 4 is assumed. The standard Student's t distribution here is truncated at the boundary values of 0 and 9. For this and other distributions, a large standard deviation eventually causes the boundary values to become the 95-percent confidence interval for the distribution, as is the case in Fig. 11. In summary, then, a Student's t distribution with appropriate boundaries will be used for each of the parameters of warhead destructiveness and target vulnerability.

The uncertainty in CEP does not fit the standard form of the uncertainty in the other parameters because CEP is a measure of the warhead impact distribution, being a simple multiple of the impact standard deviation. The uncertainty in a normal distribution's standard deviation is usually parameterized by the (square root of a) chi-square distribution.[25] Applying this formulation for 25 missile

[25]In this formulation, the true CEP (E(CEP)) is related to the calculated (nominal) $\overline{\text{CEP}}$ by the equation:

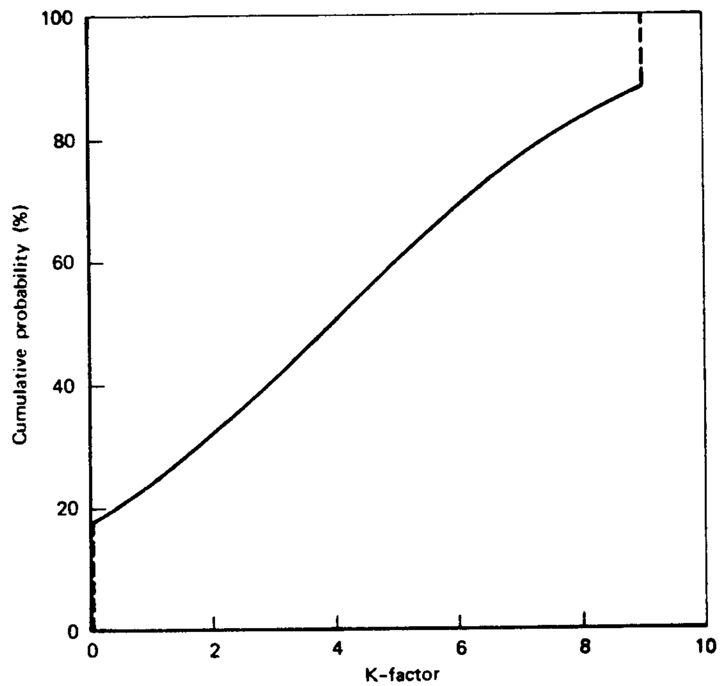

Fig. 11—Truncated cumulative Student's t distribution for uncertainty in K-factor, s = 4

flight tests (an arbitrary choice) produces the uncertainty distribution for CEP shown in Fig. 12. Of particular note is the skewed nature of this distribution, with the long tail on the high side of CEP. Figure 13 shows the cumulative probability of this distribution, with the 95-percent confidence interval running from 470 feet to 840 feet. For more flight tests,[26] this interval would narrow; for fewer, it would

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$$E(CEP) \leq \overline{CEP} \cdot \sqrt{\frac{D.F.}{{}_{\alpha}X^{2}}}$$

where D.F. is the number of degrees of freedom (the number of test shots minus one), and ${}_{\alpha}X^2$ is the chi-square statistic for the α probability (e.g., 95 percent) and D.F. degrees of freedom.

[26]This naturally assumes that all flight tests counted together come from the same "population" (that they are homogeneous samples). In other words, all tests counted together must use the same test range and the same or exactly equivalent hardware (missile, warheads, chaff packages, and guidance system) and software (which deter-

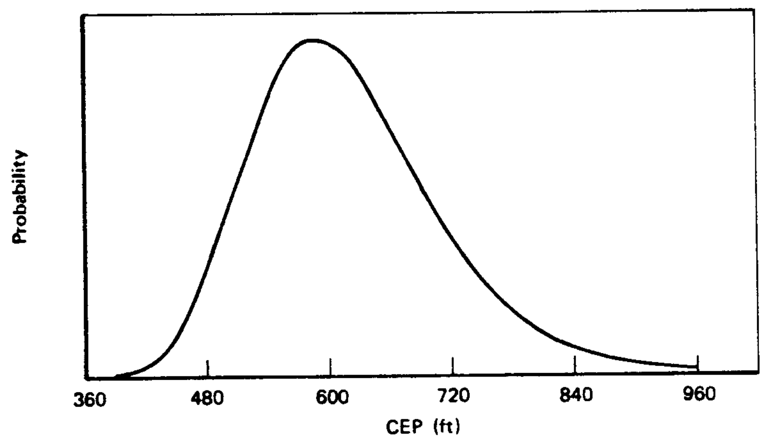

Fig. 12—Uncertainty distribution of CEP after 25 flight tests

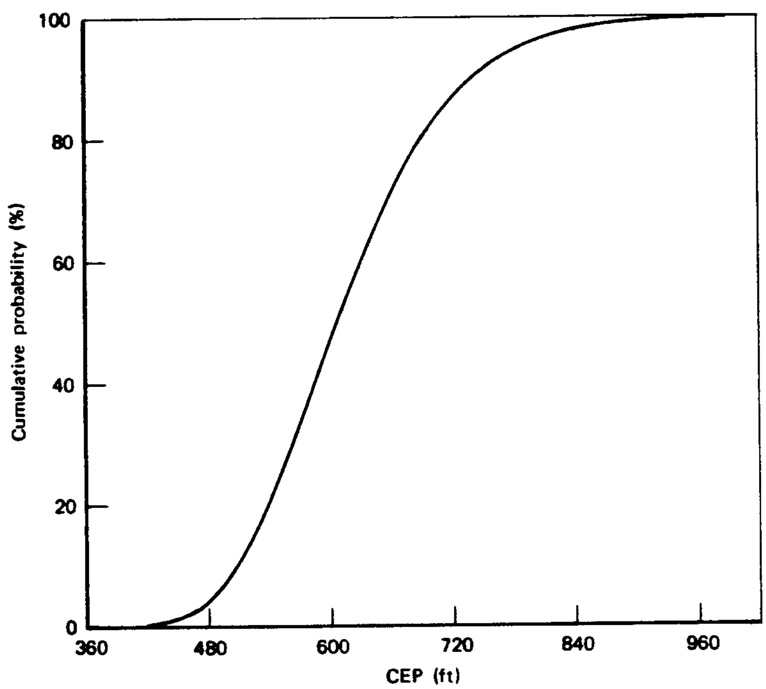

Fig. 13—Cumulative distribution of CEP uncertainty after 25 flight tests

increase. Thus the primary determinant of the amount of uncertainty in the CEP is the number of flight tests that have been conducted on missile accuracy (that is, more tests lead to a better estimate of the CEP).

Finally, the uncertainty in the systematic bias must also be handled somewhat differently. For a specific test range and a specific sample of flight tests, the bias is naturally calculated as the distance between the "mean point of impact" and the actual target. The uncertainty in this distance is thus the uncertainty in the mean point of impact, which is a function of the standard deviation of impact (a multiple of the CEP) divided by the square root of the number of flight tests. For homogeneous test samples on a specific test range, then, the uncertainty in the bias is also primarily a function of the number of flight tests.

In reality, the uncertainty in the mean value of systematic bias is not so simply estimated. The factors that apparently cause systematic bias (including gravitational anomalies and atmospheric conditions) will tend to vary with the missile's trajectory, and neither the United States nor the Soviet Union has ever tested ICBMs on operational trajectories over the *North Pole.* Therefore, in an actual counterforce strike, systematic bias will probably be an "unknown" parameter, for which a value and an uncertainty range can only be estimated[27] (and may vary from target to target as well[28]). The probability distribution

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mines trajectories and corrective actions for errors). Tests in which any of these aspects differ may have different impact distributions, and would therefore have to be statistically examined separately.

[27]Former Secretary of Defense Schlesinger alluded to these problems in stating: "Meanwhile, we in the United States must accept the fact that while our test-range accuracies with all-inertial guidance systems have shown marked improvement over the years, there remain considerable uncertainties about the extent to which accuracies will degrade on operational trajectories, especially since the world is not a perfect sphere." Department of Defense, *Annual Report, Fiscal Year 1976 and Fiscal Year 1977,* p. II-8. This suggests that the CEP, as well as the bias, could degrade on operational trajectories. In *U.S.-USSR Strategic Policies* (Hearings before the Subcommittee on Arms Control, International Law and Organization of the Committee on Foreign Relations, United States Senate, 1974, pp. 15-17), Schlesinger discussed this point in more detail, and gave by example the results of a 0.1 n mi and a 0.2 n mi "operational degradation" in the CEP, without mentioning bias. However, it is typical of planners to "include" bias in CEP; further, Schlesinger's description of the problem suggests that the major difficulty is in the systematic bias (gross error) as opposed to the CEP (which would increase the dispersion of impacts).

[28]For example, atmospheric conditions (wind speed or amount of ice or water in the air) can affect the actual impact point, and would be expected to vary from target to target. Gravitational anomalies could affect each missile/target pairing with a different missile trajectory. Target location errors would also be a target-to-target variation that would affect gross miss, though these errors may be correlated for targets in the same vicinity. In each of these cases, while we may understand what the source of the error is, we apparently have difficulty in estimating its impact on systematic bias. There may be other errors, as well, for which we do not even know the source.

shown in Fig. 14[29] (with the cumulative distribution shown in Fig. 15) will be used to estimate systematic bias when it is "unknown." This distribution is chosen because its mode ("most likely") value for systematic bias is the same as the nominal value assumed above (200 feet), and yet the tail of the distribution is sufficiently long to reasonably cover most possible values of bias. Thus, while the average bias according to this distribution is 400 feet, this distribution will be considered consistent with the nominal bias estimate of 200 feet, since most traditional strategic assessments employ "best estimate" (or "most likely") parameters rather than averages across an assumed uncertainty distribution.

THE EFFECT OF UNCERTAINTY IN EACH PARAMETER

Using the uncertainty distributions developed above, it is possible to assess the effect of uncertainty in each parameter upon the resulting SSPK. In doing so, we first examine how varying amounts of uncertainty in each parameter affect the resulting estimates of SSPK. These assessments show the relative sensitivity of SSPK to these uncertainties.[30]

Figures 16 and 17 show the impact on SSPK of uncertainty in target vulnerability. In these figures, the abscissa measures the amount of uncertainty (the size of the standard deviation) considered, while the curves represent a 95-percent confidence interval for the SSPK.[31] As should be expected, the confidence intervals become wider as the standard deviation of the parameter increases. From Fig. 16 it can be seen that, while the SSPK upper bounds for the VN and K-factors are roughly equivalent for the same absolute standard deviation, the SSPK lower bound for the VN is much lower.[32] The

[29]This is a chi-square distribution with four degrees of freedom multiplied by 100. Thus the median value of the distribution is 200 feet, and the mean is 400 feet.

[30]These calculations are done from the attacker's point of view, and thus assume that the height of burst is fixed at what he perceives to be a conservative optimum—1000 feet.

[31]"UB" stands for the upper bound of the confidence interval, and "LB" for the lower bound.

[32]Naturally, there is no reason to suspect that these standard deviations will be of the same magnitude, and thus the exact comparison of these confidence intervals must await a determination of the relative uncertainty in these parameters, as developed below. Also, the choice of a normal distribution, especially for the VN, may not be entirely appropriate since an upper bound on hardness may exist, or it may be more likely that the hardness is lower, not higher, than the nominal value. An upper bound of 3000 psi on the hardness of cement (and thus silos) is given in John M. Collins and Anthony H. Cordesman, *Imbalance of Power: Shifting U.S.-Soviet Military Strengths*, Presidio Press, San Rafael, California, 1978, p. 51.

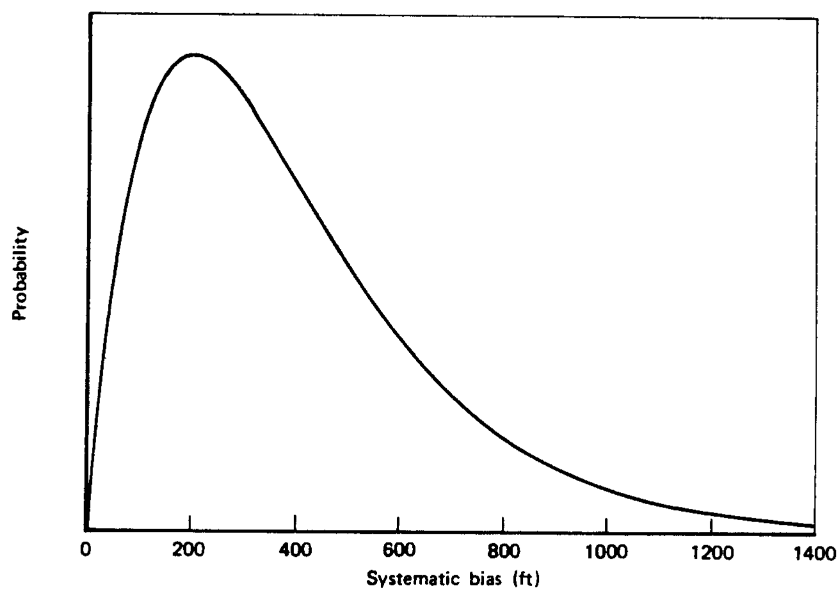

Fig. 14—Uncertainty distribution assumed for unknown systematic bias

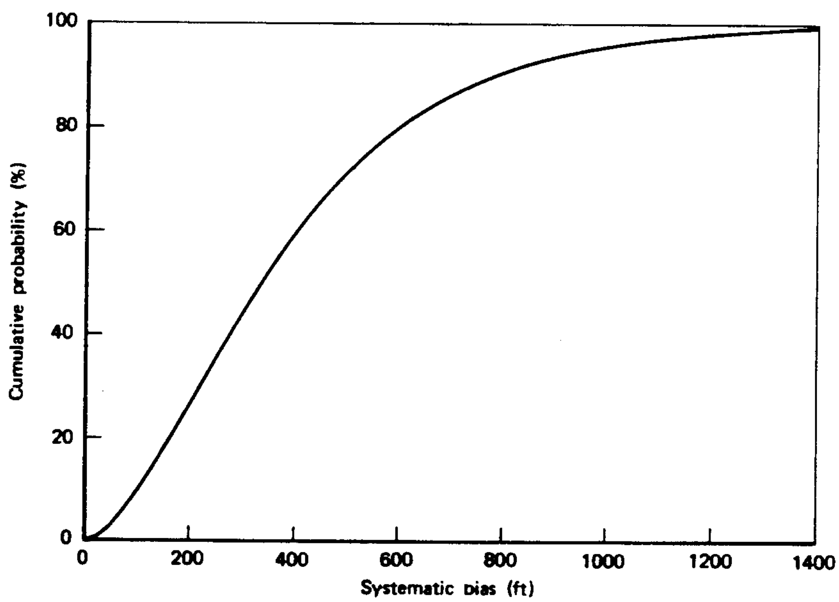

Fig. 15—Cumulative distribution assumed for unknown systematic bias

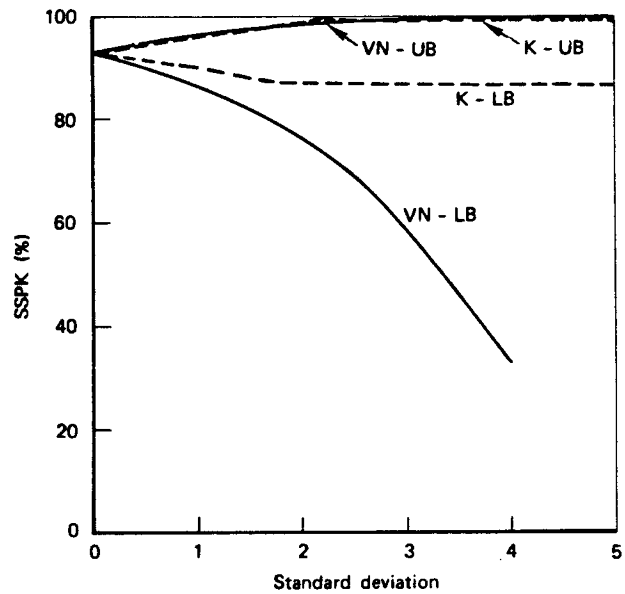

Fig. 16—SSPK confidence intervals for vulnerability number uncertainty

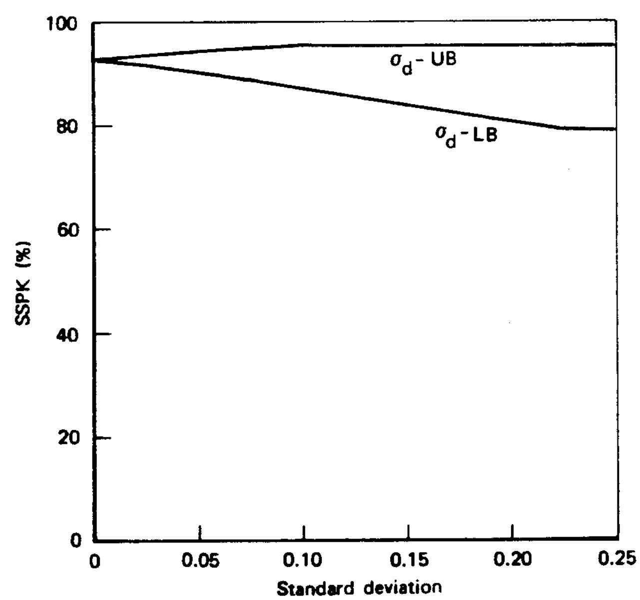

Fig. 17—SSPK confidence intervals for damage sigma uncertainty

SSPK upper and lower bounds for the K-factor quickly reach a constant value because the K-factor is valid only over a certain interval ($0 \leq K \leq 9$), and thus runs into boundary limitations as explained above. The location of these extreme bounds will be related to the nominal K-factor, because higher values for the nominal K-factor would increase the difference between the expected target hardness and the maximum possible target hardness (which would occur at $K = 0$, or at no reduction in target hardness due to overpressure pulse duration). Thus, for a nominal K-factor of 9 which has a 93-percent SSPK, the uncertainty range could fall to an SSPK of 40 percent, the lower bound of the confidence interval falling just above the lower bound for the VN.

Figure 17 gives the SSPK-confidence interval for the damage sigma. The interval is very narrow throughout the range shown. Further, its upper and lower bounds have the same sort of boundary limits as described above, causing both to eventually reach a constant value. High values of the damage sigma correspond to the lower bound (as can be seen in Fig. 3), and low values of the damage sigma produce its upper bound.

Figure 18 shows the relationships among various levels of uncertainty in the warhead destructiveness parameters and the uncertainty in SSPK. Once again, the curves indicate upper and lower bounds of a 95-percent confidence interval for SSPK. For an equivalent level of uncertainty in these parameters, uncertainty in the weapon radius function clearly has the greatest effect on SSPK,[33] and uncertainty in height of burst has the least effect.[34] Since the height of burst is placed at a near optimum value, the SSPK upper bound for height of burst is, consistently, the nominal value of SSPK. The lower bound for yield falls off sharply because low values of yield affect the weapon radius by (1) giving a lower value of yield to scale against, (2) by decreasing the pulse duration and thus increasing effective target hardness, and (3) by causing the constant 1000-foot height of burst to be much too high for an effective airburst at small yields.

Figure 19 shows the impact of the number of flight tests on the uncertainty in SSPK.[35] While the uncertainty in SSPK due to the

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[33]For small changes that do not affect the optimum burst height, this is naturally true since the weapon radius scales with yield to the one-third power. Thus, to match a 50-percent decrease in the weapon radius, yield would have to drop to one-eighth of its initial value.

[34]However, both random variations and uncertainty in the height of burst can degrade warhead accuracy, potentially causing a greater decrease in SSPK. See App. C for details.

[35]Once more, it is important to note that such flight tests must be essentially identical. Any changes, especially ones designed to improve accuracy (which is what a flight test program is designed to do), will cause a different impact distribution, with its "tests" counted separately from those of any other configuration.

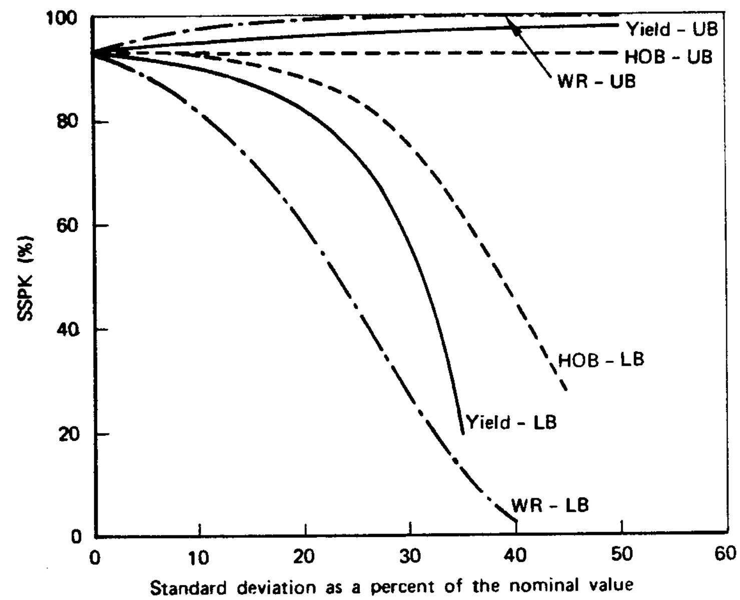

Fig. 18—SSPK confidence intervals for warhead destructiveness uncertainty

simple bias error is fairly quickly resolved (largely in about 10 to 20 tests), much higher numbers of tests are required to effectively bound the impact of CEP uncertainty to the same level (indeed, about four to six times as many tests are apparently required to gain a comparable SSPK lower bound of 80 percent or greater). In any case, at the very least about 20 to 30 tests of a given system are necessary to bound both of these uncertainties over yet untested trajectories. The systematic bias distribution of Figs. 14 and 15 produces a 95-percent SSPK confidence range of 58 to 94 percent (with systematic bias ranging from 1100 feet down to 50 feet).

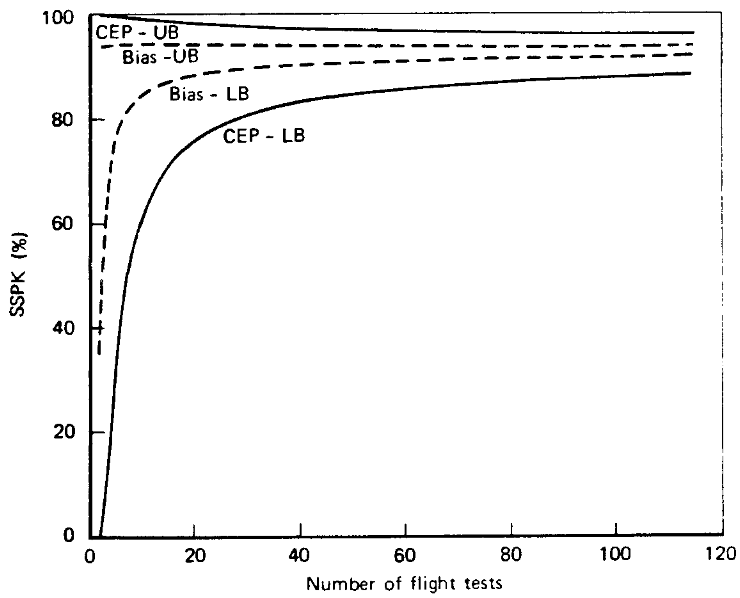

Fig. 19—SSPK confidence intervals for warhead accuracy uncertainty

COMBINING THE SSPK PARAMETER UNCERTAINTIES

Having examined the effect of uncertainty in each parameter on SSPK, it now becomes important to combine all of the uncertainties into a single calculation.[36] There are two difficulties in doing so: (1) the problem of combining various uncertainty distributions with a damage function to give a distribution of outcomes, and (2) the need to establish the level of uncertainty that should be used for each parameter. The first difficulty is addressed by applying Monte Carlo simulation to the uncertainty distributions. The second difficulty is handled by applying the available strategic literature on parameter uncertainties, and by making guesses when no other data are available.[37] To ensure that fairly representative choices are made, a

[36]In the estimates of survivability uncertainty hereafter, random variations are ignored because they play a relatively small part in the overall level of uncertainty, as argued in the previous section. For more information on the effect of random variations, see Apps. A and C

[37]For estimates of a generally different kind that are available to give some guidance

low and a high level of uncertainty will be considered. Further, as stated above, because some of the uncertainties differ from the Soviet and U.S. points of view, a rough comparison will be made of each.[38]

In evaluating the effect of parameter uncertainty on SSPK above, uncertainty was considered in only one parameter at a time. Since SSPK is a monotonic function of each of the parameters (except height of burst), it was possible to draw the corresponding uncertainty distribution for SSPK by directly applying the SSPK formulation to the uncertainty distribution for any given parameter. However, once uncertainty in more than a single parameter is taken into account, no such simple procedure can be used to determine the uncertainty distribution for SSPK. Instead, given the potential complexity of any analytic function that even approximates this distribution, Monte Carlo simulation will be used to estimate it. The Monte Carlo procedure takes a sample from the uncertainty distribution of each parameter under consideration, and uses these sample values to determine a sample SSPK outcome. This process is repeated 500 times, producing 500 "equally probable" estimates of the SSPK, from which an uncertainty distribution for SSPK can be drawn. This sample distribution should estimate most of the uncertainty distribution quite well, given the large number (500) of samples taken; however, even with this number of samples, it is hard to estimate with precision the extreme values (the "tails") of the distribution. Consequently, conclusions that focus on the "tails" (about the last 5 percent in either direction) of the distributions will be avoided.

Estimates of uncertainty in the parameters of survivability are usually given as ranges, and fail to specify the type of uncertainty included. For example, it is commonly stated that the actual yield of a nuclear weapon will be within 10 percent of its stated yield. Unfortunately, this range of 10 percent on either side of the stated yield is not associated with any specific level of confidence (for example, are we 90-, 95-, or 100-percent sure that the yield will fall within this range?). Further, this uncertainty is due to some mixture of random variations (for example, two warheads of the same type could explode with 90 percent and 110 percent, respectively, of the stated yield) and uncertainty in the mean value of the parameter (for example, all warheads have exactly the same yield, but that yield could be anywhere from 90 percent to 110 percent of the stated value). To deal with such estimates, it will be assumed that such ranges are 95-percent confidence

on a few parameters, see *Counterforce Issues for the U.S. Strategic Nuclear Forces*, pp. 61-73.

[38]U.S. estimates of Soviet parameters are more uncertain than Soviet estimates of those values because the U.S. does not have direct access to Soviet test data. The Soviets face somewhat the same difficulty in assessing U.S. parameter values.

ranges, and thus that the standard deviation of the distribution is roughly one-half of the range (5 percent for yield, for example) on either side of the stated value. Further, it will normally be assumed that the stated ranges express uncertainty in the mean value of a parameter, rather than random variations.[39]

Table 2 shows the nominal parameter values and estimates of the uncertainty in their mean values. For target vulnerability, the uncertainty ranges are obtained largely by inference. For example, in App. C it is argued that the nominal damage sigma may well be off by 0.1 unit or more, suggesting a low estimate of 0.05 for its standard deviation (one-half an assumed 95-percent confidence range of plus or minus 0.1 unit). For the K-factor, simply the fact that it is stated only in integer terms makes its minimum uncertainty plus or minus 0.5 unit, or a standard deviation of 0.25. That the Soviets would be somewhat more uncertain about the nature of U.S. silos seems probable, and thus they are given twice as high a value for the standard deviation of their uncertainty in the K-factor. For the VN, DIA seems to indicate it has a minimum uncertainty of plus or minus 1 unit or a standard deviation of 0.5,[40] and it is once again assumed that the Soviets' uncertainty would be twice as great. For each of these factors, the high uncertainty is simply assumed to be twice the low values.

For warhead destructiveness, DIA states that the overpressure at a given range is uncertain to plus or minus 20 percent.[41] This range corresponds to a weapon radius uncertainty of roughly plus or minus 10 percent, or a standard deviation of 5 percent, which will be used for the low estimate of weapon radius uncertainty. Because that uncertainty could be much greater,[42] a standard deviation of 10 percent was chosen for the high value of uncertainty. For yield, DIA's *Physical Vulnerability Handbook* suggests an uncertainty of plus or minus 10 percent or a standard deviation of 5 percent, which is used

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[39]This assumption may overstate the uncertainty in the mean value by including what is really some random variation in the stated uncertainty range. Therefore, this type of information will be used only when no other estimate of the uncertainty in the mean value of a parameter is available.

[40]DIA, p. 35.

[41]Ibid. In H. L. Brode, *Height of Burst Effects at High Overpressures*, The Rand Corporation, RM-6301-DASA, July 1970, the overpressure uncertainty is given as $\pm$ 10 percent up to 1000 psi (pp. 14, 19), and the random variation as upward of $\pm$ 40 percent (p. 14). This source also shows some data suggesting that the normal "near ideal surface" curves may substantially overestimate real range (see especially Brode's Figs. 4 and 5, pp. 8-9). More recent work indicates a slightly higher uncertainty level (a ground range of plus or minus 5 to 10 percent) below about one-half the old optimum burst height, and a still higher level of uncertainty above it because of a double shock waveform. See H. L. Brode and T. G. Lewis, "Implications of Recent Airblast Studies to Damage of Hardened Structures," in W. J. Hall (ed.), *Structural and Geotechnical Mechanics*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1975, pp. 55-69, esp. p. 61.

[42]See comments in the previous footnote.

Table 2

SSPK PARAMETER UNCERTAINTIES

Parameter	Nominal Value	Uncertainty in the Mean Value[a]			
		Soviet Low	U.S. Low	Soviet High	U.S. High
VN	43	1.0	0.5	2.0	1.0
K-factor	4	0.5	0.25	1.0	0.5
Damage sigma	2	0.05	0.05	0.1	0.1
Yield	1000 kt	5%	10%	10%	20%
Height of burst[b]	1000 ft	5%	5%	—	—
Weapon radius	WR_o	5%	5%	10%	10%
CEP	600 ft	50 tests	25 tests	20 tests	10 tests
Bias[c]	200 ft	50 tests	25 tests	$100 \cdot \chi_4^2$	$100 \cdot \chi_4^2$
Student's t degrees of freedom		9	9	4	4

[a]Standard deviation for first six parameters, based on Student's t distribution with the degrees of freedom shown in the last row.

[b]High uncertainty forces the Soviets to use a groundburst.

[c]Low uncertainty ranges are as shown in Fig 19; high uncertainty uses the distribution of Figs. 14 and 15.

as the low Soviet value. As indicated in App. C, that uncertainty can be increased by uncertainty in the power of yield used, so that double this value (a standard deviation of 10 percent) is used as the high Soviet value. Since the United States can only roughly guess Soviet yields, the U.S. uncertainty on Soviet yield is assumed to be twice as great as the Soviet uncertainty. Finally, a guess of a 5-percent standard deviation is used for the low uncertainty in the mean height of burst, and a groundburst (with no uncertainty) is used for the high uncertainty case (since high uncertainty in height of burst makes groundbursts preferable).[43]

A Student's t distribution will be used to simulate the uncertainty in target vulnerability and warhead destructiveness. For the low uncertainty level, this distribution will assume nine degrees of freedom (ten tests). The high uncertainty level will assume half as much testing, and thus only four degrees of freedom.[44]

In terms of warhead accuracy, it is generally recognized that the

[43]These values are considerably lower than those shown for height of burst uncertainty in *Counterforce Issues for the U.S. Strategic Nuclear Forces*. The relative advantages of groundbursts and airbursts are described in App. C.

[44]The standard deviations given herein are the actual mean value standard deviations; the difference in the degrees of freedom between high and low uncertainty values is used only to spread the Student's t, and not to modify the standard deviations stated in Table 2.

Soviets test their ICBM systems fairly extensively.[45] Therefore, it will be assumed herein that the Soviet low estimate of CEP and systematic bias uncertainty is based upon 50 operational tests of each system used in the attack. For the U.S. low perception of Soviet uncertainty in accuracy, only 25 tests will be assumed, since the United States may not accurately monitor some of the Soviet tests, and in any case, may not be able to perfectly interpret any data it did collect. On the high side, the systematic bias distribution introduced in Figs. 14 and 15 will be used for the reasons discussed above. Only 20 tests will be assumed in formulating the Soviets' high uncertainty in CEP, since they could use a relatively untested (a new or recently modified) system in the attack. The U.S. high uncertainty in CEP will again assume half as many tests.

The effect of these parameter uncertainties on SSPK is shown for the low-uncertainty levels in Fig. 20 and for the high-uncertainty levels in Fig. 21.[46] Looking first at the high-uncertainty levels, the Soviet distribution is clearly a very risky, indeed probably too risky, outcome. In it, the Soviets can only be 90-percent sure of getting at least a 55-percent SSPK, even though the average of the Monte Carlo simulations is 78 percent, which is, in turn, quite a bit worse than the nominal outcome of 93 percent or the 94-percent SSPK of the

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[45] *U.S.-USSR Strategic Policies*, p. 47, where 59 tests are shown for the 1972 to early-1974 time period on the four new Soviet missile systems (SS-16, SS-17, SS-18, and SS-19). All but one of these missiles came in both single-warhead and MIRV configurations; therefore, if the 1973 total of 42 tests for the seven total configurations is typical, about six flights per system should be expected each year that each system is in development. Recent testing of Soviet ICBMs seems to be at a somewhat higher pace, however, with 13 SS-18 and 12 SS-19 flights from January to mid-October 1978 ("Soviet Strategic Missile Testing Continues at High Pitch," *Soviet Aerospace*, October 1978, p. 39). Still, this higher number of tests appears to be due to development of a new, more accurate missile system as early as April of 1978. See Clarence A. Robinson, Jr., "Soviets Boost ICBM Accuracy," *Aviation Week and Space Technology*, April 3, 1978, p. 14. The Soviets tested yet another SS-18 model beginning in October 1978: "Soviets Testing New Model of SS-18 ICBM," *Soviet Aerospace*, October 23, 1978, p. 47. Thus, in reality, the "high" uncertainty estimate of 20 tests on a *specific missile configuration* is probably fairly accurate.

It is also important to note that many of these flights may be tests of different configurations (for research and development purposes), and would thus not necessarily add to an assessment of accuracy since they would not come from a homogeneous population. Thus, in the Minuteman flight test program, flights are divided into a number of categories, including R&D flights and operational tests, the latter of which would tend to give the needed accuracy information. For both Minuteman II and Minuteman III, 50 percent to 60 percent of all tests have been operational, and even these have been divided into different phases with fewer than 40 tests in any given phase. See *Vandenberg AFB Launch Summary*, Headquarters, First Strategic Aerospace Division, Vandenberg AFB, California, July 1978, with Changes 1 and 2 through December 1978.

[46] Note that the variabilities discussed in Apps. A and C are ignored in this and subsequent analyses because their effect is relatively minor, and because they introduce significant complications into the calculations if they are to be taken into account.

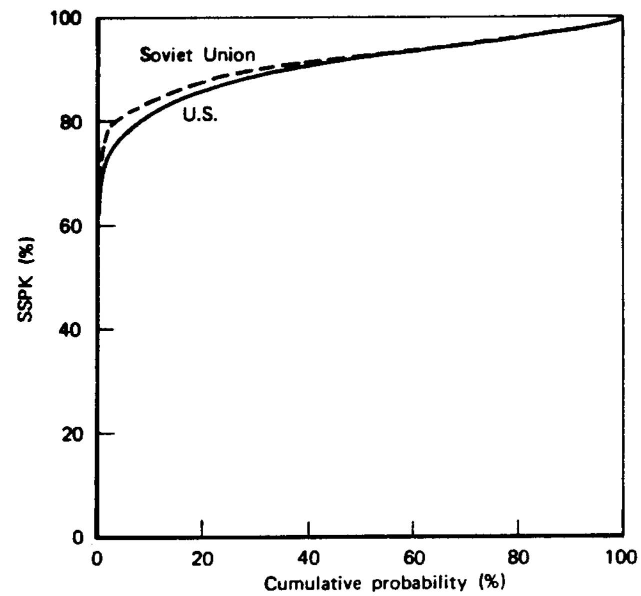

Fig. 20—Soviet SSPK distribution for low uncertainties

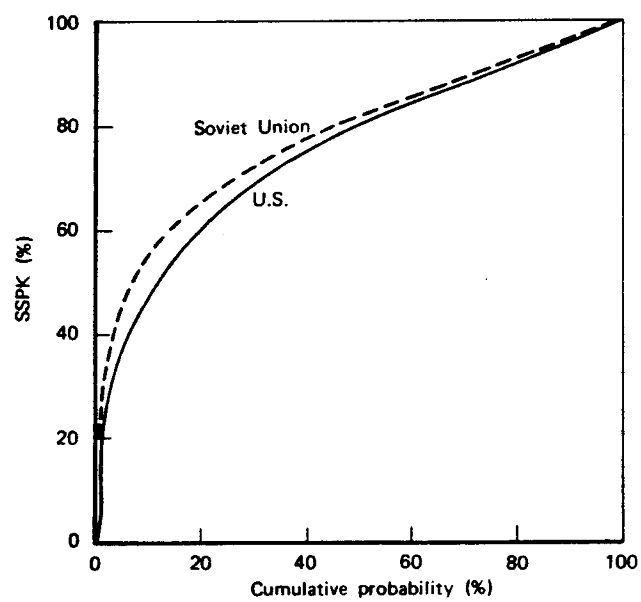

Fig. 21—Soviet SSPK distribution for high uncertainties

traditional model. Still, the Soviets do have a 28-percent probability that the SSPK would be above 90 percent, which would be a fairly good outcome if obtained. From the U.S. point of view, the average SSPK outcome is 75 percent, which is much better than the 93-percent "nominal" SSPK, but is still very risky since it would appear that there is only a 75-percent probability that the SSPK would be less than 90 percent. In short, even though the Soviets would be extremely unsure of their countersilo attack effectiveness, the United States could not be sure that threat is insignificant.

Turning, then, to the low-uncertainty case, the Soviets are now much more certain of their capabilities, being 95-percent sure that their SSPK is at least 80 percent (though this SSPK may yet be too low). Further, their average SSPK over these uncertainties is 91 percent, not very different from the nominal 93-percent SSPK or the traditional model's SSPK of 94 percent. The United States in its turn is now 63-percent sure that the Soviet SSPK is at least 90 percent, and therefore cannot ignore what would appear to be a substantial Soviet threat. In comparison, then, with the high-uncertainty threat, the low-uncertainty threat is one that the Soviets can begin to believe in, and about which the United States must really begin to worry. Still, even the low-uncertainty levels do not *guarantee* to either side that there really is a substantial threat in terms of SSPK. Of course, SSPK is only one part of the total kill probability. The other parts are developed in the next section.

IV. AN INTEGRATED METHODOLOGY FOR CALCULATING ICBM SURVIVABILITY

The determination of silo survivability comprises essentially four dimensions: single-shot kill probability (SSPK), multiple-shot kill probability, warhead arrival, and fratricide. The single-shot kill probability was developed in detail in Sec. III. This section details the other three dimensions and their problems and uncertainties. The multiple-shot kill probability (PK—the complement of PS) is the combination of the SSPKs for each warhead detonating at a particular silo. Warhead arrival is the probability that each warhead targeted against a particular silo arrives at or near that silo and detonates if no other warheads have previously detonated in that vicinity. Finally, fratricide is the probability that an arriving warhead is destroyed by various effects produced by the explosion of earlier warheads. All of these factors are combined into an integrated assessment of ICBM survivability, including the uncertainties associated with each factor.

THE KILL PROBABILITY FOR MULTIPLE SHOTS

For the SSPKs and missile reliabilities that apply to current types of warheads, multiple warheads must be targeted at each missile silo to obtain a high kill probability. This is especially true because fratricide may well eliminate some percentage of the otherwise reliable warheads. To calculate the kill probability (PK) of these multiple shots, the number of warheads that arrive and detonate at a given target is first calculated, and then their SSPKs are combined. To develop this formulation, the procedures for combining SSPKs will first be described and analyzed for uncertainties, after which the relationship of reliability and then fratricide will be added.

The normal procedure for combining the damage of multiple weapons is to "compound" the damage. That is, as formulated in Sec. II for the traditional model, if the damage caused by each warhead is independent of the damage caused by every other warhead, then the PS for n identical warheads is:

$$PS = SSPS^{n}$$

or, in terms of the multiple-shot kill probability:

$$PK = 1 - (1 - SSPK)^n$$

More generally, for n different warheads,

$$PK = 1 - \prod_{i=1}^{n} (1 - SSPK_i)$$

This formulation follows from the cookie-cutter damage function of the traditional model. As stated in Sec. II, the above formulas for the traditional model and n identical warheads can be expressed as:

$$PK = 1 - 0.5^{n\left(\frac{LR}{CEP}\right)^2}$$

This equation raises an interesting point. If the basic cookie-cutter damage function is taken to its logical conclusion, it is clear that unless the warhead landing closest to the target (out of n multiple, identical warheads) lands within the lethal radius and thus kills the target, the target will survive. Assigning multiple warheads to the target has the effect of making it more probable that at least one warhead lands within the lethal radius, which is equivalent to "reducing the CEP" of the warhead that lands closest to the target. Mathematically, it can be shown that the "CEP" of the closest warhead (CEP_1) is:[1]

$$CEP_1 = \frac{CEP}{\sqrt{n}}$$

Thus, PK becomes:

$$PK = 1 - 0.5^{\left(\frac{LR}{CEP_1}\right)^2}$$

which is exactly equivalent to the previous equation for PK.[2] Thus, simple damage-compounding in the traditional model is equivalent to ignoring all warheads but the one falling closest to the target. In turn, adding multiple warheads reduces the "CEP" of the closest warhead. For example, a single, reliable, detonating warhead with a 600-foot CEP has the same kill probability as four identical, reliable, detonating warheads that each have a 1200-foot CEP, since the

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[1]See App. D for this derivation.

[2]The use of CEP_1 in this equation ignores the damage caused by the other warheads, since they will not affect the target unless the closest warhead would kill the target; therefore, they add nothing. This formulation necessarily assumes a zero systematic bias.

"closest" of these four will have an effective CEP of 600 feet. Figure 22 shows the CEP and warhead tradeoff for several PK values of potential interest (assuming the traditional model). Especially for lower values of PK, additional warheads per silo can greatly "improve" the CEP of the warhead falling closest, and can therefore overcome fairly poor initial CEPs. In any case, this formulation uses reliable, detonating warheads, and can change significantly once delivery probability and fratricide are taken into account.

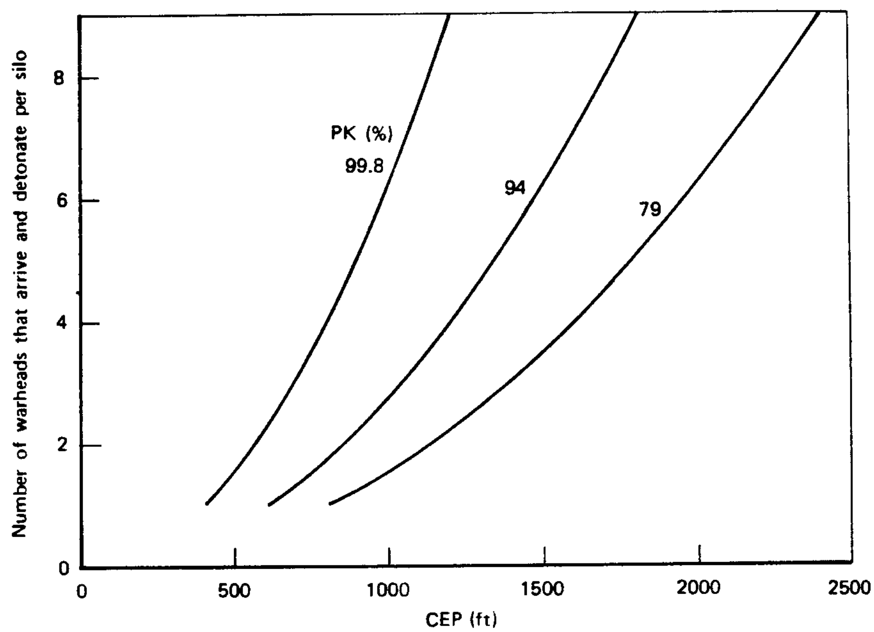

Fig. 22—Number of warheads vs CEP for constant PK levels

Once we shift to a non-cookie-cutter damage function ($\sigma_d \neq 0$), the proper formulation for multiple-shot damage is not as obvious. In part, this change is due to the fact that the formulation will vary with the sources of random variation in the damage function, and these sources are generally not specifically identified. For example, if σ_d is entirely a function of target-to-target variations (that is, some targets are harder than others), then the effective hardness of any individual target is fixed, and damage against *each individual* target can be handled as a cookie-cutter function, with the closest warhead determining the kill

probability (with relatively more of the hard targets surviving any given attack). If, however, σ_d is entirely a function of warhead-to-warhead variations,[3] then damage can be simply compounded, since the effect of each warhead is independent of the effect of every other. The difference between these formulations is illustrated in Fig. 23, which shows the multiple-shot kill probability for three different CEPs, otherwise assuming the nominal attack data (including $\sigma_d = 0.2$, but assuming a zero systematic bias). This figure shows that compounding the damage produces a slightly higher PK than does using the SSPK of the closest warhead only, since the latter procedure ignores the potential contribution to the PK of all other warheads, whereas the former approach counts that contribution. Perhaps surprisingly, though, this difference is rather small, becoming significant only as the SSPK falls and the number of warheads used rises.[4] However, since compounding the damage is the normal procedure even in the vulnerability number system, PK estimates will be somewhat overestimated by that procedure since the damage sigma is usually greater than zero and target-to-target variations do contribute to the damage sigma.

A final problem may have the opposite effect. A silo damaged by a nuclear explosion, though not destroyed, will be more vulnerable to subsequent attacking warheads. In that event the SSPK may increase for warheads after the first, and may thus increase the overall kill probability above that calculated by simple compounding or focusing on the closest warhead. This author is unfamiliar with any effort to quantify how large an effect this could be, and thus is forced to retain the standard assumption of damage compounding.[5] When combined with the opposite effect of compounding suggested above, this effect will add some (though probably very little) uncertainty to the estimates of PK beyond those captured in the remaining calculations of this section.

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[3]Warhead-to-warhead variations can include variations in the terrain around the target, since explosions downhill from a target increase the overpressure delivered at a given distance, and vice versa. This is a warhead-to-warhead variation if the terrain is sloped such that the effect will vary with variations in impact points.

[4]If bias is factored in, the difference is about the same as shown in Fig. 23 for an equivalent SSPK unless the bias is of the same size as or larger than the CEP, in which cases the difference is somewhat greater than shown.

[5]The choice of combining damage by compounding is made because it falls roughly mid-range between the different procedures for combining damage, and because it is generally much simpler than any other procedure.

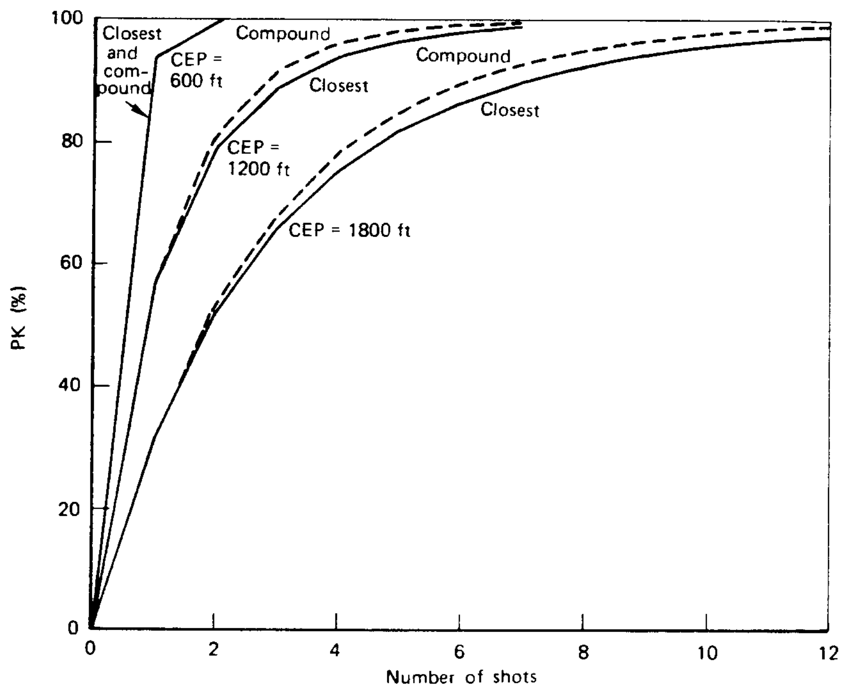

Fig. 23—Compound vs closest warhead value for PK

ARRIVAL PROBABILITY

Arrival probability (or delivery probability) is the terminology generally used to represent the probability that a warhead (1) survives an enemy attack occurring before it is launched, (2) launches and reliably separates from its delivery vehicle, (3) penetrates enemy defenses, and (4) detonates over the target. For a Soviet ICBM first strike against present or projected U.S. silos (without ABM), the survival and penetration aspects are of no concern, leaving only the normal reliability terms (launch, boost, warhead separation, and warhead detonation) as part of arrival probability.

A weapon that fails to "arrive" on target (including detonation) cannot damage the target. Therefore, the total kill probability of a given warhead can be no greater than its arrival probability. For a single warhead, the arrival probability (PA) should be independent of the SSPK, such that the net expected kill probability equals the product of these two factors, or:

$$PK = PA \cdot SSPK$$

Even for a weapon with an SSPK of close to 100 percent, arrival probability, which is nominally assumed to be 90 percent, will prevent a single warhead from having a very high expectation of damage (above 90 percent) against a silo. Indeed, if anything, the literature tends to suggest that the reliability of a missile could be a fair amount lower than 90 percent,[6] but probably could not be much higher.[7] If, however, multiple warheads could be assigned to each silo with *independent* probability of arrival, the probability that at least one will detonate on target (PDT) increases dramatically for reasonable ranges of reliability, soon approaching 100 percent:

$$PDT = 1 - (1 - PA)^n$$

This relationship is depicted in Fig. 24 for (n =) 1, 2, and 4 warheads. As this figure shows, two warheads nearly double the probability that at least one warhead arrives if the arrival probability is very low, while increasing PDT to a maximum of 25 percent over PA (from 50 percent to 75 percent) and pushing PDT close to 100 percent for arrival probabilities of 80 percent or better. Four warheads give much higher values for PDT, pushing it close to 100 percent for arrival probabilities of 60 percent or better. Thus, multiple independent warheads help to guarantee that at least one warhead detonates on target even if the delivery of each warhead is fairly unreliable.

The same kind of formulation can be extended more generally to the kill probability. For n identical warheads, PK can be expressed as:[8]

$$PK = 1 - (1 - PA \cdot SSPK)^n$$

Thus, as with PDT, multiple warheads can help overcome a low arrival probability or a low SSPK. This is illustrated in Fig. 25, where the warheads required to produce a 90- or 99-percent PK are plotted

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[6]See, for example, Steinbruner and Garwin, p. 150, which quotes 67.5 percent, and Edward N. Luttwak, *Strategic Power: Military Capabilities and Political Utility,* The Center for Strategic and International Studies, Georgetown University, 1977, p. 60, which gives 73 percent.

[7]"Because of the ban on atmospheric testing of nuclear weapons and other operational limitations, it is impossible to measure reliability through complete tests. Instead, information is collected from flight tests of missiles with inert warheads, from tests of components, and from underground nuclear tests, and combined to form estimates of overall system reliability. These estimates are not available to the public; however, one can speculate that a system with a reliability of less than 50 percent would clearly be unsatisfactory, while engineering complexity of typical systems would place an upper limit of 90 to 95 percent on system reliability." Alton H. Quanbeck and Barry M. Blechman, *Strategic Forces: Issues for the Mid-Seventies,* The Brookings Institution, Washington, D.C., 1973, p. 73. That assertion is probably true, given the limited amount of testing in the development of strategic systems, though better performance might be possible with more thorough development programs.

[8]This formulation assumes that multiple-shot damage can be simply compounded.

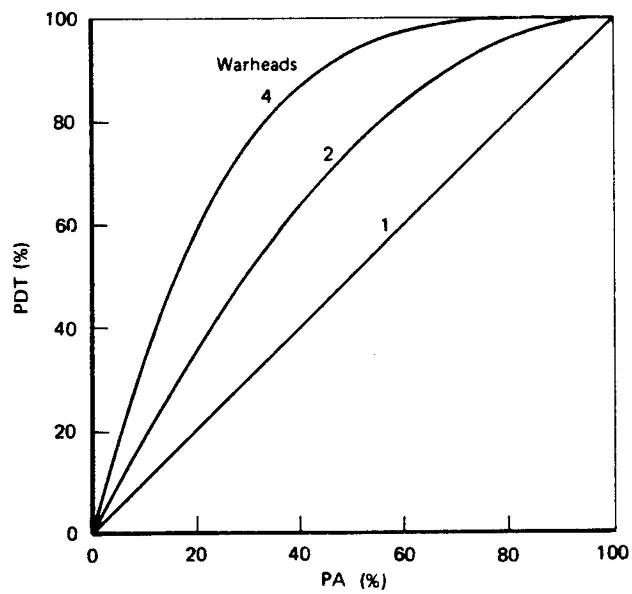

Fig.24—Effect on arrival of multiple shots

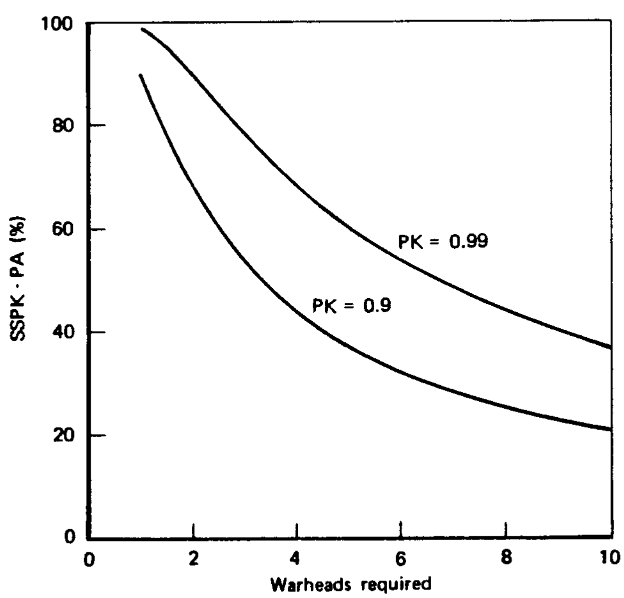

Fig. 25—Warheads required for high values of PK

against the arrival probability times the SSPK of the individual warheads. Still, if these numbers are fairly small (below 50 percent), a very large number of warheads may be required to obtain a high value of PK.

To deal with reliability more comprehensively, the correlation between the arrival of warheads at a target must be examined. This is done by dividing reliability into its four components, corresponding to the four parts of a warhead's flight: (1) launch reliability, (2) booster reliability, (3) warhead separation, and (4) warhead detonation. For MIRV warheads on the same missile, the reliability of the missile through steps 1 and 2 will be completely correlated for each warhead, and the reliability of step 3 will be partially correlated.[9] Alternatively, whether or not a warhead detonates after proper separation (step 4) should be independent of what happens to any other warhead on the same booster.[10] Further, even the reliability from steps 1 to 3 should be independent for warheads coming from different missiles. Therefore, to obtain the independent reliability used in the formulations above, warheads aimed at a single silo must be cross-targeted from different missiles. If, instead, the warheads aimed at a single target come from the same missile, then the reliability must be looked at in two terms: the dependent component (r_d, from steps 1 to 3) and the independent component (r_i, from step 4 and possibly from step 3). Thus:

$$PA = r_d \cdot r_i$$

In this sort of arrangement, the earlier formulations become:

$$PDT = r_d - r_d \cdot (1 - r_i)^n$$

$$PK = r_d - r_d \cdot (1 - r_i \cdot SSPK)^n$$

For completely independent warheads, r_d equals 1, and these equations simplify to their earlier forms. Alternatively, for warheads that are completely dependent, r_i equals 1, PDT equals r_d, and PK equals the probability that all n warheads arrive and detonate (r_d) times the probability that all of them kill the target. In other words, if the reliability were ever completely dependent, multiple warheads would not help overcome the reliability problem, but would help increase the PK by compounding damage when the warheads did arrive.

[9]That is, incorrect separation of one warhead from the booster may affect the remaining warheads.

[10]This ignores the risk of total warhead detonation failure forcewide due to design error, since operational tests should uncover such problems.

UNCERTAINTY IN ARRIVAL PROBABILITY

As stated above, only reliability contributes to arrival probability in the context of a Soviet first strike on undefended U.S. silos. The various parts of reliability noted above are generally observable during the flight-test program of a given missile system (steps 1 to 4),[11] or during the underground nuclear warhead tests (step 4). After a number of tests (T), in which U successes and A failures occur (T = U + A), the expected reliability is simply:

$$r = \frac{U}{U + A}$$

Since each test is an independent event, the uncertainty in reliability should be binomially distributed, with variance equal to:[12]

$$\mathrm{var}(r) = \frac{r \cdot (1 - r)}{T}$$

This variance leads to the distribution of possible reliability values shown in Fig. 26 for ten flight tests. Note that this distribution is truncated at 95-percent reliability, this being a reasonable upper bound for such complex systems as ICBMs.[13]

Figure 27 shows the effect of uncertainty in reliability on PK when combined with the high U.S. SSPK uncertainties of Table 2 for a two-warhead-per-silo attack.[14] These values compare to the almost 98-percent PK of the traditional model. The upper curve assumes that both warheads arrive and detonate independently (PA = r_i), whereas the lower curve assumes complete dependence of the two warheads (PA = r_d). The two curves differ by as much as about 8 percent, and by 6 percent on the average. Thus the payoff to using multiple warheads from different missiles in this case is fairly small. In either case, though, there is a substantial uncertainty in the kill probability, somewhat as shown for the SSPK in Fig. 20, and the PK through most of the range is much lower than the traditional model PK. Figure 28 shows the same curve for low U.S. uncertainty, assuming that both

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[11]Warhead detonation includes activation or failure of the warhead fuze. This is determined in the flight test program, though failure is certainly not correlated between warheads on the same missile unless a forcewide failure occurs.

[12]Actually, since both flight tests and underground tests are involved, and since these tests are independent, a compound binomial distribution would be more exact. However, since warhead detonation is apparently only a small part of the total reliability term, it will be included as a "simple" part of the other reliability components. See Luttwak.

[13]See Quanbeck and Blechman. A normal distribution for the uncertainty is assumed here because of its ease, despite the fact that ten tests are so few that a binomial distribution would be more appropriate statistically.

[14]Uncertainty in reliability is based upon the number of flight tests shown in Table 2 for the accuracy parameters.

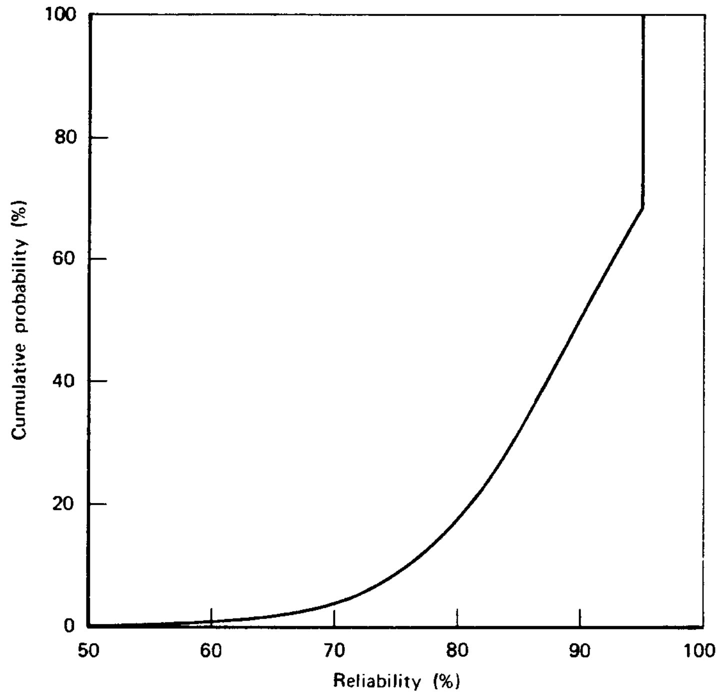

Fig. 26—Uncertainty distribution for reliability

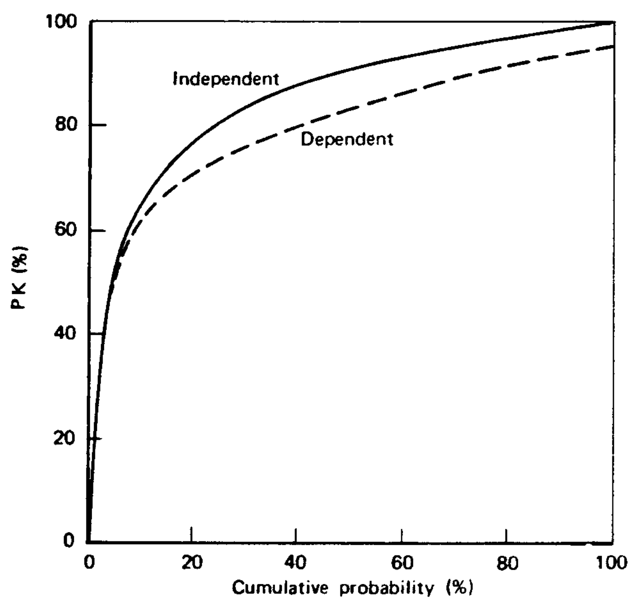

Fig. 27—High uncertainty in Soviet PK for
a two-warhead attack

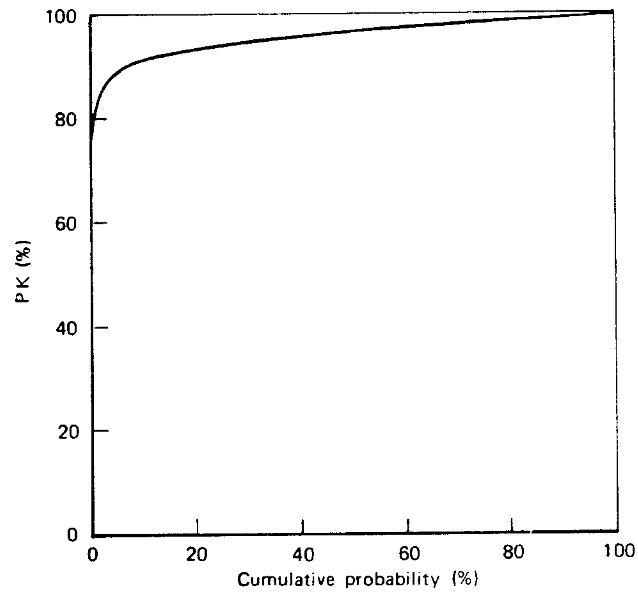

Fig. 28—Low U.S. uncertainty in Soviet PK for a two-warhead attack

warheads are independent, achieving a high average PK, and showing relatively little uncertainty. Still, the PK is lower than the traditional model PK with a 70-percent probability, and may be much lower.

As noted above, extra warheads assigned per target help to hedge against poor performance. This is shown again in Fig. 29, where even with the high uncertainties, four independent warheads greatly decrease the uncertainties of an attack. They produce an average kill probability of 95 percent, as opposed to 85 percent for two warheads, and do quite well against the U.S. ICBMs with about an 80-percent to 90-percent confidence. Even the use of four warheads will not help much, however, in the low-probability cases of extremely low PK, because of poor performance of the attacking missile systems.

One of the ways to compensate for low reliability is to reprogram reserve missiles to take the place of missiles that have failed in flight. Doing so requires a monitoring system to determine which missiles have failed, so that their targets can then be assigned to reserve missiles that are launched as soon as possible. Two difficulties confront this procedure. First, while it seems quite possible to monitor

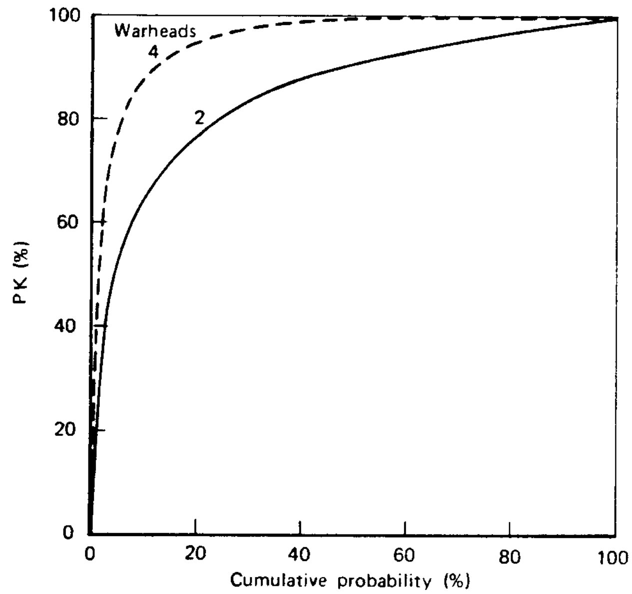

Fig. 29—High U.S. uncertainty in Soviet PK for two attack levels

reliability of a missile through boosting (step 2), it is not so easy thereafter. Further, failures in a MIRV system during warhead separation or in detonation are more a warhead-by-warhead problem; while it is relatively easy to have one missile completely replace another, it is not so easy to have a reserve missile replace failed warheads from *several different* earlier missiles. Therefore, most analyses of reprogramming divide reliability into a reprogrammable portion (r_p) and a nonreprogrammable portion (r_n):[15]

$$r = r_p \cdot r_n$$

The second problem with reprogramming is that the missiles assigned to take the place of a failed missile may themselves fail; therefore, some consideration must necessarily be given to a second, and perhaps third, reprogramming (by the third time, very few new failures should develop).

[15]See, for example, Davis and Schilling, pp. 218-230, and also Steinbruner and Garwin, pp. 148-150. When the term "nonreprogrammable" is used, it does not necessarily mean that those warheads lost *could not* be replaced; rather, it means that determining which did fail and then replacing them is a much harder problem.

Because of these two problems, it is unlikely that reprogramming will guarantee warhead delivery. Therefore, we will assume that reprogramming replaces some fraction of the warheads that failed, improving reliability to r′. The fraction 1 of improvement in reliability will be defined as:

$$1 = \frac{r' - r}{1 - r}$$

Thus, in moving from 90-percent (r) reliability to 95-percent (r′) reliability by reprogramming, 50 percent (1) of the original failures have been reliably replaced.[16]

Figure 30 shows the effect of 50-percent reprogramming for the two-warhead-per-silo attack, assuming U.S. high uncertainties. Reprogramming improves PK about 2.5 percent on the average, and up to 4 percent at the most, which is not much of an improvement.[17] Even 100-percent reprogramming (not shown in Fig. 30) increases the kill probability only about 4.5 percent on the average, and it is unlikely that such a high level of reprogramming could be obtained. Further, reprogramming here has very little effect on the steep, high-risk part of the curve, where one would hope that a hedge against uncertainty like reprogramming might help. Therefore, for systems with basically high reliability, the effect of reprogramming is fairly negligible.

SYSTEM DEGRADATIONS

For MIRV systems, the accuracy and reliability numbers given are almost always those for the first warhead released from the missile. The later warheads may have degradations in accuracy and (possibly) in arrival probability as well, but those degradations are rarely modeled in strategic analysis because it is somewhat difficult to do so and because the degradations are apparently not well parameterized.

They are also not usually considered in countersilo attacks because their effect is relatively minor, as shown in Fig. 31. In this calculation, it is assumed that an eight-warhead SS-18 attacks the U.S.

[16]Note that, according to the definition of nonreprogrammable reliability,

$$r' \le r_n$$

Therefore:

$$1 \le \frac{r_n - r}{1 - r}$$

[17]Naturally, if the nominal reliability were less than 90 percent, reprogramming would make more of a difference.

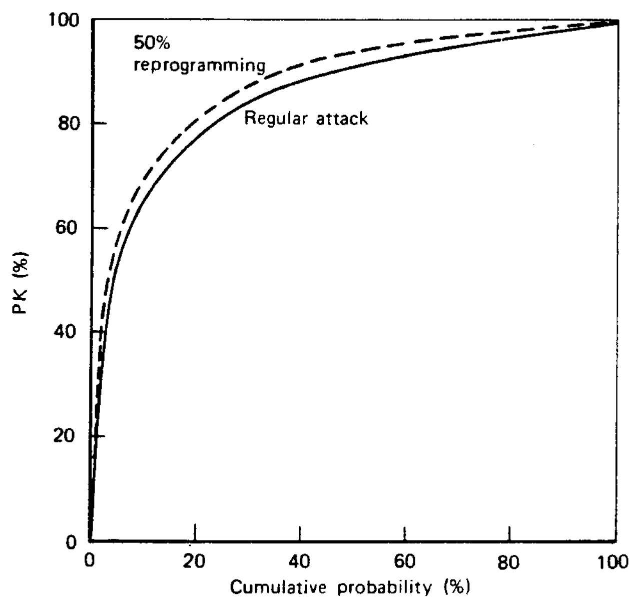

Fig. 30—High U.S. uncertainty in Soviet PK, showing the difference made by reprogramming

silos, and that each warhead after the first is an extra one-percent less reliable (the eighth warhead is thus a nominal 83-percent reliable), and has an extra 25 feet added to its CEP (the eighth warhead thus has a nominal 775-foot CEP). As a result, the kill probability drops up to 7 percent, with a 4.5-percent average. While this drop is not very great, it exceeds the improvement shown earlier by a 50-percent reprogramming. Both reprogramming and system degradations will be ignored in subsequent nominal calculations in order to simplify the calculations. However, it will be shown later that these system degradations can become a very important problem when multiple protective shelter basing induces the Soviets to fractionate their MIRV payloads into a great number of very small warheads, as opposed to eight warheads of the one-megaton class.

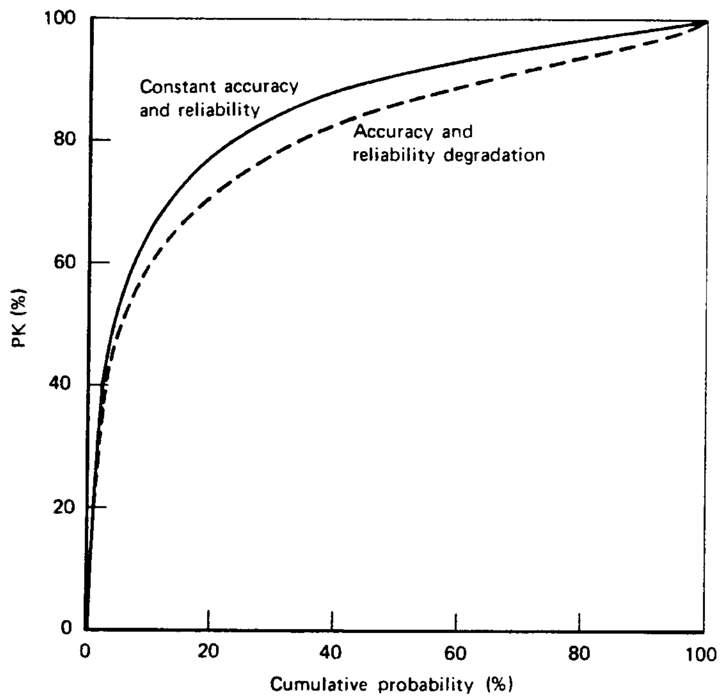

Fig. 31—High U.S. uncertainty in Soviet PK, assuming degradation of MIRV accuracy and reliability

FRATRICIDE

Over the last few years, as concern in the United States about the survivability of land-based ICBMs has been mounting, articles have appeared in a wide variety of journals suggesting that the problem of "fratricide" will prevent the Soviets from being able to deliver a highly effective counterforce attack.[18] To repeat, fratricide is the destruction of an incoming warhead by debris or nuclear effects coming from a previous nuclear detonation in the same area. As a

[18]See, e.g., Steinbruner and Garwin, and Lt. Col. Joseph J. McGlinchey and Dr. Jakob W. Seelig, "Why ICBMs Can Survive a Nuclear Attack," *Air Force Magazine*, September 1974, pp. 82-85. Other authors apparently believe that improved technologies (and smaller yields?) will eventually mitigate the fratricide problem. See, for example, Collins, p. 51.

result, warheads that would otherwise reliably detonate on target are lost from the attack just as though they were unreliable. The debris and effects of previous nuclear detonations can also affect the accuracy of a warhead, either by blowing it off its path (blast) or by eroding the warhead (with debris impacts) at a rate faster than expected, thus altering its ballistic characteristics and trajectory. Unfortunately, no test data are available for evaluating the effect of prior detonations because the United States has never tested multiple, near-simultaneous bursts. Theoretical models are therefore the only recourse. Further, since the accuracy effect is much harder to parameterize, it will be ignored herein.

There are basically two kinds of fratricide, referred to here as "local" and "area." Local fratricide is the destruction of an incoming warhead by the detonation of an earlier warhead *assigned to the same target;* thus it can occur only if more than one warhead arrives at the target. In this connection, some experts have argued that at most two, and perhaps only one, warhead can realistically be expected to detonate at any given silo. Area fratricide is defined as the destruction of an incoming warhead by the detonation of an earlier warhead *assigned to a different though nearby (generally uprange) target.* Because most of this problem lies in an uprange direction,[19] most analyses try to overcome it with a "rollback" attack, where the targets farthest downrange are hit first, and the attack then progresses in the uprange direction. Of the two kinds of fratricide, most experts point to local fratricide as the more significant.

One of the most popular recent articles on ICBM survival, that of Steinbruner and Garwin, concentrated on the problem of fratricide, and developed a physical model of the problem. The authors all but exclude local fratricide from consideration: "It is assumed that the warheads of the red force are destroyed if they fly through the cloud stem of a nuclear explosion within five minutes of detonation, and thus it is assumed that the attack plan requires a delay of six minutes between the arrival of separate warheads at the same target."[20] That local fratricide is excluded is shown by the fact that even when only one (not necessarily reliable) warhead is assigned per target (thus ruling out local fratricide), Steinbruner and Garwin show that fratricide would kill about 18 percent of the reliable warheads.[21]

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[19]That is, an incoming warhead flies relatively low over uprange targets because of its low reentry angle. The debris clouds and other effects of earlier detonations can rise well above this flight path, causing fratricide.

[20]Steinbruner and Garwin, pp. 150-151.

[21]Ibid., p. 174, where 115 out of 655, or 18 percent, do not explode because of fratricide.

Therefore, the primary effect that they are capturing is area fratricide. Using their various tables and the reliability and SSPK that they assume, this author calculated the average numbers of reliable warheads surviving fratricide and fit a curve to those numbers versus the reliable warheads arriving per silo.[22] (See Fig. 32.) Somewhat surprisingly, the average percentage of warheads surviving fratricide ($\bar{F}$) falls to a fairly high, constant level. It does so because Steinbruner and Garwin expand the time required for the attack to keep fratricide within bounds, and the expansion apparently reaches a steady-state situation where a given number of detonations per hour enforces a fixed percentage of attrition. This pattern of $\bar{F}$ implies a rather unusual pattern, however, in terms of the marginal percentage of reliable warheads surviving fratricide (F), as shown in Fig. 33. Of the first warheads, about 83 percent survive, but of the second reliable warheads assigned per target, only 68 percent survive (for an average of 75 percent), less than the 70-percent steady state. Thus, while the curves developed here are only approximations of Steinbruner and Garwin's results, they suggest an interesting and somewhat strange pattern of fratricide.

This author has developed an alternative estimate of fratricide that captures most directly the problem of local fratricide. This "model" assumes a lognormal distribution[23] for the probability that the ith reliable warhead arriving at a silo survives fratricide (F_i), with

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[22]Ibid., pp. 152, 154, and 174. The equation of this curve is:

$$\bar{F} = 0.7 + 0.3e^{-0.86n}$$

where $\bar{F}$ is the average fraction of warheads surviving fratricide, and n is the number of reliable warheads per silo. This curve is *very* much an approximation. Note that Steinbruner and Garwin's numbers are not always consistent: On p. 174, one warhead per silo kills 340 missiles out of 1000 attacked, or a 34-percent PK; on p. 152, 70 to 77 kills are scored out of 200 attacked, or a 35-percent to 39-percent PK. This equation is based on the mid-range numbers of p. 152.

[23]This equation is:

$$F_i = \frac{1}{2\pi} \int_{-\infty}^{\tau_i} e^{-t^2/2}\, dt$$

$$\tau_i = \frac{\mathrm{Ln}(0.5 \cdot i)}{0.3}$$

This formulation also assumes that the effect of fratricide on warhead i is independent of its effect on any other warhead (thus, if the second warhead is killed by fratricide, the third one is not necessarily doomed). Appendix E discusses this model in light of physical weapon effects.

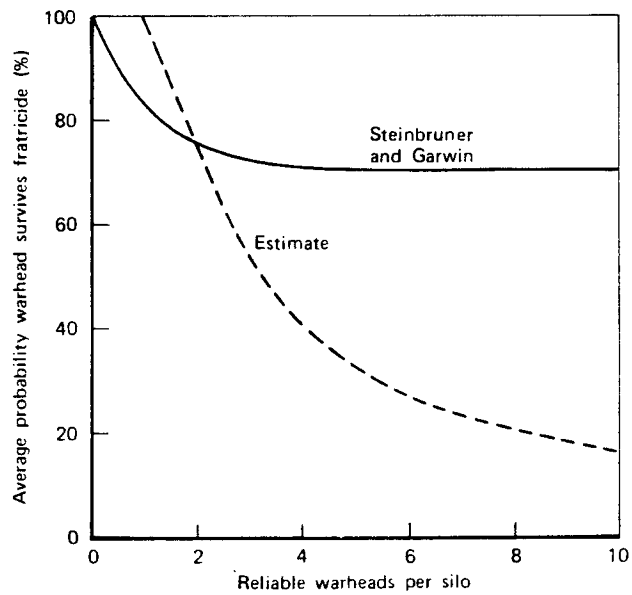

Fig. 32—Average probability that a warhead survives fratricide in two models

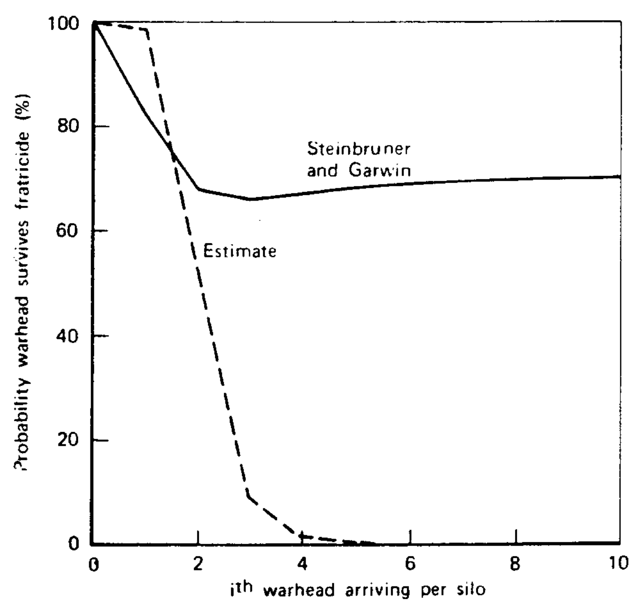

Fig. 33—Probability that warhead n assigned to a silo survives fratricide in two models

the values for F_i shown as an "estimate" in Fig. 33, and for $\bar{F}$ in Fig. 32. According to this view, very few warheads survive fratricide beyond the third reliable one arriving at each silo, and even the second and third warheads have a fairly high probability of being lost.[24] Therefore, assigning extra warheads to each silo will help guarantee that some arrive, but will not lead to numerous weapons detonating at or near that target.

UNCERTAINTY IN FRATRICIDE

A large amount of uncertainty must be associated with these two models of fratricide, especially given the lack of test data on this effect. For the Steinbruner and Garwin approach, the steady-state level of average fratricide survival is assumed to vary as shown in Fig. 34; for less than steady-state loss, this uncertainty is scaled down so that the median value of the uncertainty distribution corresponds to the appropriate value on the curve in Fig. 32. Figure 35 shows the probability that the first, second, third, and fourth warheads survive fratricide, assuming the local fratricide model introduced above. In that model, the first reliable warhead has a high probability of surviving fratricide. The second warhead's fratricide level varies across the board, and the third and fourth warheads usually will not survive (except for some low-probability assessments of fratricide that suggest they would). Admittedly, these formulations are approximate guesses at best, but they are better than assuming either that there is no fratricide or that there is no uncertainty about fratricide.

Figures 36 and 37 show the net effect of fratricide on PK for high U.S. uncertainty, with two and four warheads targeted per silo, respectively. In the two-warhead-per-silo case, the Steinbruner and Garwin estimate shows the greater degradation, involving a high estimate of area fratricide. The local fratricide model yields a generally lower

[24]This is much closer to the standard view of fratricide as this author understands it. Normally, it is assumed that at most two, and perhaps only one, warhead can be used per target without being overcome by fratricide. A good, simple description of this view is given in *Counterforce Issues for the U.S. Strategic Nuclear Forces*, pp. 11-13. It is also important to note that although neither this model nor the author's approximation of the Steinbruner and Garwin model includes the effect of yield, yield is generally recognized as a significant factor in the fratricide problem. Thus, Steinbruner and Garwin indicate that they would not expect much fratricide from 200-kt warheads (p. 165). Yield has been ignored in these fratricide models because its impact is not well known, because the yield does not vary much around the nominal one-megaton value in these calculations, and because ignoring yield makes the calculations much easier.

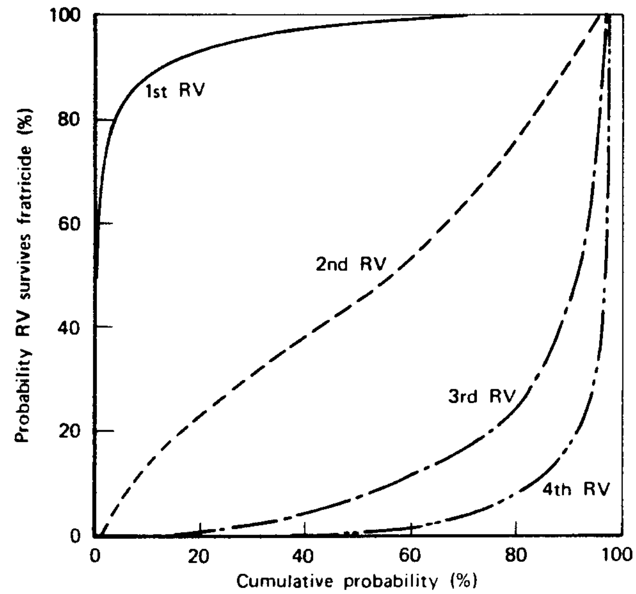

Fig. 34—Uncertainty in steady-state fratricide survival in the Steinbruner and Garwin model

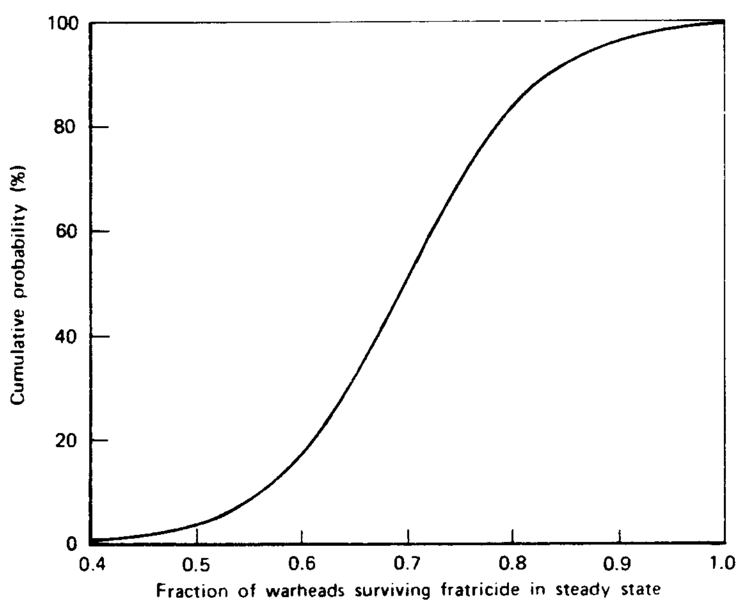

Fig. 35—Uncertainty in fratricide for the local fratricide model

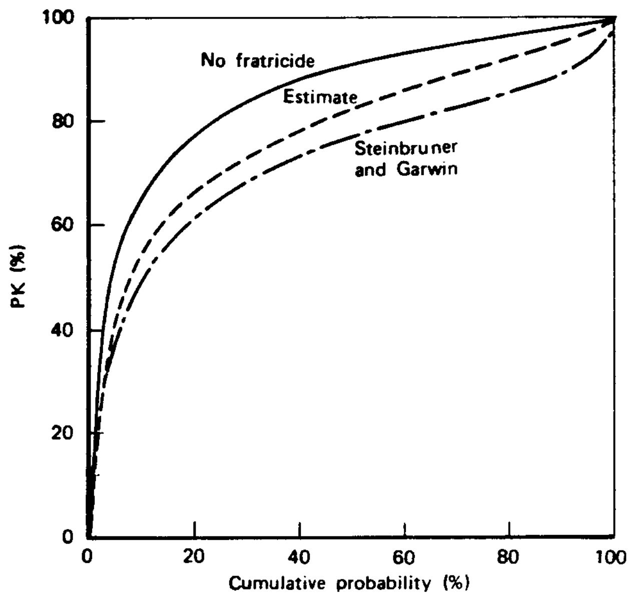

Fig. 36—High U.S. uncertainty in Soviet PK for different fratricide assumptions, 2-warhead-per-silo attack

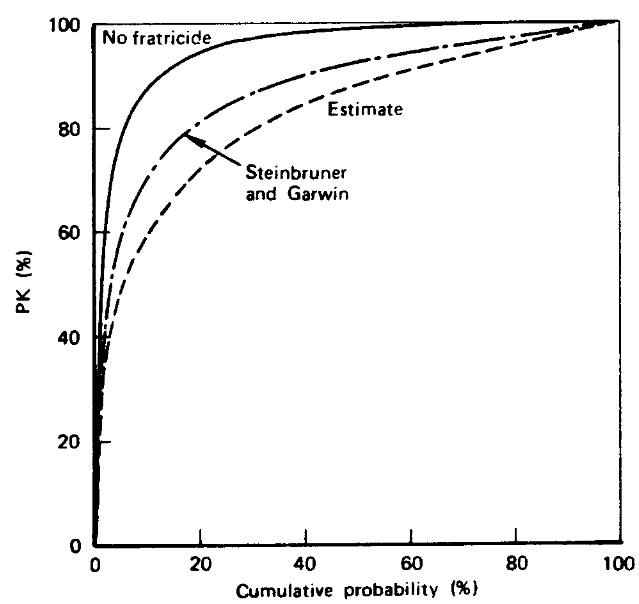

Fig. 37—High U.S. uncertainty in Soviet PK for different fratricide assumptions, 4-warhead-per-silo attack

PK estimate for four warheads targeted per silo, since this attack allocation presses against this model's rather strenuous limits on warheads that can detonate per silo. In any case, either model of fratricide degrades the PK values by a fairly large amount from the "no fratricide" calculation, making high confidence in very high damage levels next to impossible for attacks carried out in a short period of time. Indeed, the traditional model's two-warhead damage level of almost 98 percent has a less than 5-percent probability of achievement according to either fratricide model, and less than a 20-percent probability even with four warheads per silo. The relatively small changes that occur between the two- and four-warhead-per-silo allocations of the local fratricide model suggest that multiple warheads are hedging primarily against unreliability (which two warheads per silo tend to do nicely), but that they do little to overcome inaccuracy in warhead delivery.[25]

CONCLUSIONS

This section has completed the development of a methodology for assessing the vulnerability of hard silo targets to enemy attack, given uncertainties in the parameters that affect such an assessment. These calculations also reveal that uncertainty can have a strong bearing on the effectiveness of an attack. As Figs. 36 and 37 show, even an attack that would nominally be considered fairly effective may turn out to be much less effective once uncertainty is taken into consideration. Indeed, even faced with a serious Soviet threat, we can be confident that at least some U.S. silos will be able to survive, though we cannot have much confidence that any large number will survive.

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[25]Taken one step further, the local fratricide model, by making multiple warheads ineffective in overcoming accuracy problems, leaves only one means for overcoming inaccuracy: increases in yield. This points out an unfortunate weakness in the local fratricide model used here: It is not sensitive to changes in yield, even though larger-yield warheads should cause a higher amount of local fratricide. Thus, in reality, it is unclear whether increases in yield do more to overcome inaccuracy (increasing PK) or do more to increase local fratricide (decreasing PK). On the balance, since the SSPK of the first delivered warhead will increase with yield and will suffer no major increase in local fratricide, increased yield probably improves the total kill probability, though only marginally.

V. THE EFFECT OF UNCERTAINTY ON POTENTIAL ICBM BASING OPTIONS

Over the past several years, Defense Department concern about Minuteman survivability has led to an examination of a broad array of basing schemes.[1] Generically, three types of options have been considered.

The first might well be called a "dash on warning" mode, in which the missiles are moved beyond the range of nuclear effects between the sounding of tactical warning and the detonation of attacking warheads. Air-launched ballistic missiles (ALBMs) typify this basing concept, in which the aircraft that carry the ALBMs do the dashing on warning.[2] This scheme requires high confidence that sufficient tactical warning will be received (unless the vehicle is continuously moving). It also requires that the dashing vehicle have high velocity and/or reasonable hardening, and be able to launch the missile accurately.

The second basing mode considered is deep underground basing, with missiles buried in extremely deep underground caverns where they probably cannot be destroyed by even very large and accurate nuclear weapons. Once the enemy attack is over, holes could be dug to the surface through which the missiles then could be fired. This basing mode delays the U.S. attack considerably, and requires longevity in U.S. command, control, and communications and in our ability to control the area above the deep underground base.[3]

The final basing mode is generally referred to as multiple protective shelters (MPS). Here, deception is used to cover the actual location of the missile, forcing the attacker to target several possible locations. This form of basing can be expensive (as are the others, unfortunately) because it embodies a proliferation of potential launch positions, and is only as good as the deception it achieves. Further, deception makes SALT verification extremely difficult, since it is hard to prevent an opponent from knowing where the missiles are (to make

[1]"Several dozen possibilities," according to "The $100 Million Mobile Missile: The M-X and the Future of U.S. Strategic Forces," *The Defense Monitor*, August 1977, p. 4. More detail on the range of possibilities is given in William Schneider, Jr., "Survivable ICBMs," *Strategic Review*, Fall 1978, pp. 19-24.

[2]Another, much simpler but cruder, approach of this sort is to launch the missiles on warning, a recourse that has the obvious drawback of irretrievably committing the force before the exact nature of the attack may be ascertained.

[3]If this area is not controlled, munitions could be emplaced in it to destroy any hole or missile coming to the surface.

them survivable) and still make him confident that the SALT agreement is being adhered to.

Of these three types of basing options, the Air Force has given its most serious consideration to two types of MPS systems: an underground trench and either a horizontal or vertical shelter.[4] The term "shelter" is perhaps a bit misleading; in the vertical form it is essentially an "austere silo," while in the horizontal form it resembles a garage, though hardened to 600 psi (as are the "austere silo" and the trench). Either basing option would house some 200 to 300 missiles, with approximately 12 miles of trench per missile on the one hand, and 20 to 25 "austere silos" per missile on the other.[5] Both of these options produce distinct survivability characteristics, and these in turn differ somewhat from the pure silo approach analyzed above.

Based upon the above information, this section will apply the basic methodology developed in Sec. IV to a comparative assessment of three basing modes: silos, shelters, and trenches. A nominal threat of 4200 one-megaton warheads will be used to test the survivability of each option.[6] The attacks on both shelters and silos will further assume that each shelter or silo must be attacked individually because they are separated by enough distance to make it unfruitful to attack multiple targets with a single warhead. The attack on trenches will assume that warheads are equally spaced along a trench line, and that trenches are also separated by enough distance to make attacks on two neighboring trenches unfruitful. The silo and shelter calculations use the "local" fratricide estimate of Fig. 33, while the trench calculation assumes a fratricide estimate as shown in Fig. 43.

THE EFFECT OF UNCERTAINTY IN SOME BASIC PARAMETERS

Using these attack data, Figs. 38 to 42 show the relative impact on PK of changes in some of the more important parameters for the

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[4]Philip J. Klass, "MX Basing Studies Show Vertical Silo Preference," *Aviation Week and Space Technology*, June 19, 1978, pp. 22-23.

[5]Ibid.; and Robinson, "MX Deployment Urged for Parity," p. 15. For the purposes of this report, 300 ICBMs and 20 austere silos per ICBM will be used, or 6000 total. Since the calculations in this report were performed, the MX system has been defined as 200 missiles with 23 shelters each, or 4600 total.

[6]Robinson, "MX Deployment Urged for Parity," p. 15, uses a 4120-warhead attack, which has been rounded up to 4200 because this number would come from a simple multiple (700) number of the SS-19 with six one-megaton warheads. The 4200 warheads are applied, alternatively, to the 1000 Minuteman silos or the MX system. In an attack against MX, no allocation is made against the probably 800 Minuteman missiles still deployed, though an adequate number of Soviet warheads would probably be available for such an attack even after the commitment of 4200 warheads to MX. The 1980s Soviet force size is discussed in more detail below in the section on MIRV tradeoffs.

standard silo system and the two MPS alternatives. Figure 38 clearly shows that the trench concept is very sensitive to uncertainty in hardness,[7] while the silos are much less sensitive, and the shelters hardly sensitive at all. Figure 39 shows a similar pattern of sensitivity for yield. The relative sensitivity of trenches is due to the fact that they are a continuous target, with the PK increasing in a roughly linear manner with the lethal radius, which in turn increases as the VN decreases, or as the yield increases. The almost complete insensitivity of shelters to changes in vulnerability or yield is due to the fact that a single nominal warhead will destroy a shelter at which it arrives with nearly a 100-percent probability unless the shelter is hardened well beyond 600 psi or the yield falls well below one megaton. For a lower hardness or higher yields, no change in PK occurs because the nominal warhead would already kill the shelter.

Figures 40 and 41 show the sensitivity of the basing modes to accuracy. Here, the harder target set—the silos—is more sensitive to changes in both CEP and systematic bias, though both trenches and shelters are nearly as sensitive (somewhat less so to CEP). For low values of CEP, the trench is more sensitive than shelters to uncertainty in CEP because the weapon radius is still sufficient to kill any point target, whereas increases in CEP do slightly degrade coverage of a line target. For higher values of CEP, the shelters are relatively more sensitive because misses become significant, whereas with the trench, at least some of the large "misses" are actually along the trench line (or close to it), and thus result in less degradation of effectiveness. For the systematic bias calculations, the trench curve shows one possible extreme: if the bias is exactly perpendicular to the trench. If the bias is exactly along the trench, however, bias will produce essentially no degradation in PK. Thus, for a trench, bias can have very different effects depending upon the orientation of the trenches to the systematic bias error. This suggests that trenches should be laid in various directions to guarantee that the attacker's bias causes him at least some loss in PK.

Finally, Fig. 42 shows the effect of changes in reliability on the survivability of ICBMs in the various basing modes. For the 4200-warhead allocation, silos are very insensitive to changes, since many reliable warheads are already lost to fratricide. Indeed, reliability lowers PK significantly only when it begins to deny some silos the one or two warheads that will detonate, and this effect apparently does not

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[7]Here, the MPS systems (trench and shelter) are defined as having a VN that is a constant value of 7 less than the VNs of silos. Thus the basic VN of 36P4 is equivalent to 550 psi for the MPS systems (37P4 is 660 psi, so 36P4 was chosen as being closer to 600 psi).

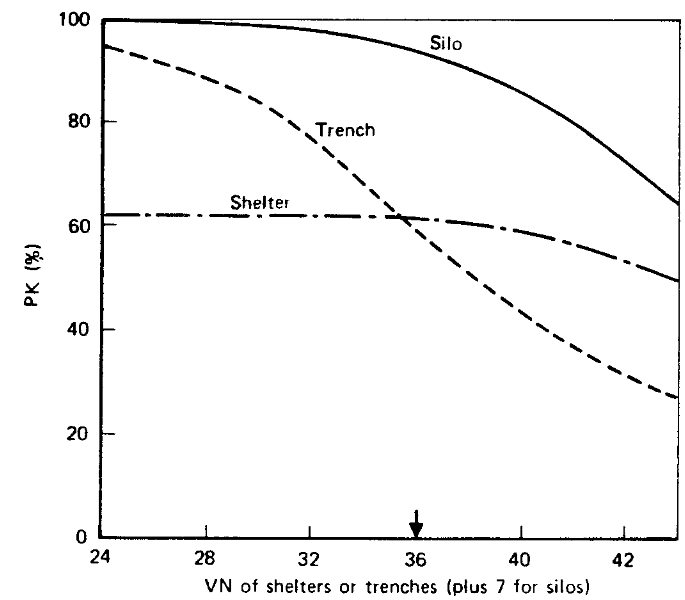

Fig. 38—Relationship between MAP VN and PK

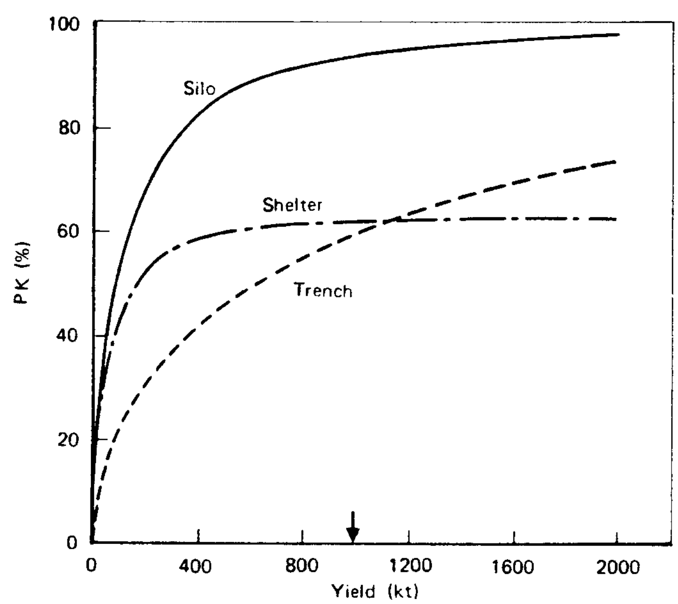

Fig. 39—Relationship between yield and PK

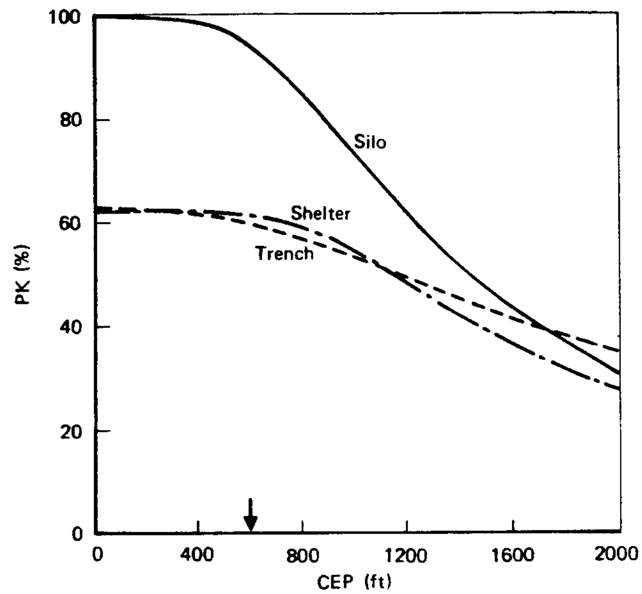

Fig. 40—Relationship between CEP and PK

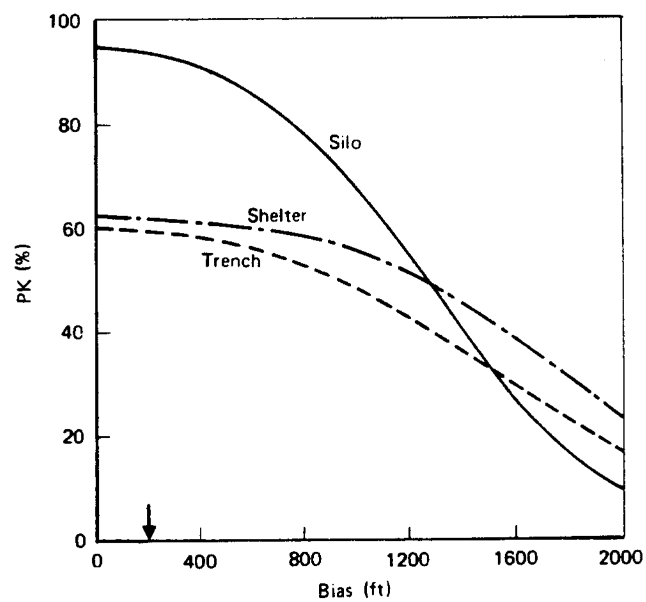

Fig. 41—Relationship between bias and PK

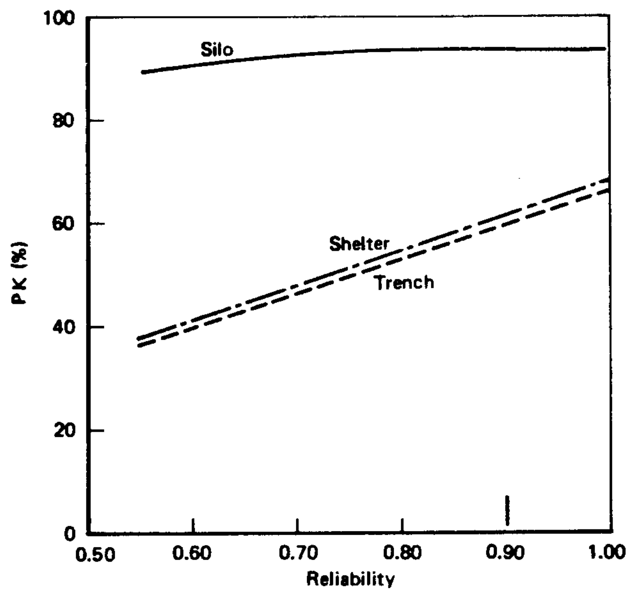

Fig. 42—Relationship between reliability and PK

set in until reliability falls below about 75 or 80 percent (and even then the effect is relatively insignificant). The effect of reliability on both shelters and trenches is, for this weapon allocation, essentially linear and equivalent, since greater reliability leads to an equivalent increase in warheads delivered to what were previously uncovered targets. The sensitivity of trenches is slightly lower because neighboring warheads provide a very limited amount of coverage for unreliable warheads at this level of attack.

Figure 43 shows the fratricide assumption made for the trench system.[8] In it, warheads targeted at a great distance from each other cause very little fratricide. However, as more warheads are allocated, their separation along the trench line becomes smaller, and interference eventually becomes severe. This choice of a fratricide model is extremely arbitrary and probably much more uncertain than the fratricide model used for silos and shelters. Further, these particular values impose a maximum limit on PK of about 86 percent

[8]In this figure, "scaled distance" refers to the distance between the points at which warheads are targeted, divided by yield (in megatons) to the one-third power. This division roughly normalizes or "scales" the distance to the weapon effects.

that can be obtained against a trench with the nominal parameters used (allowing attack size to vary).[9] Therefore, uncertainty in trench fratricide will be captured by assuming that the levels of warhead loss shown here are median, and using a normal distribution around these values with a standard deviation equal to one-half of the median warhead losses at each separation distance.

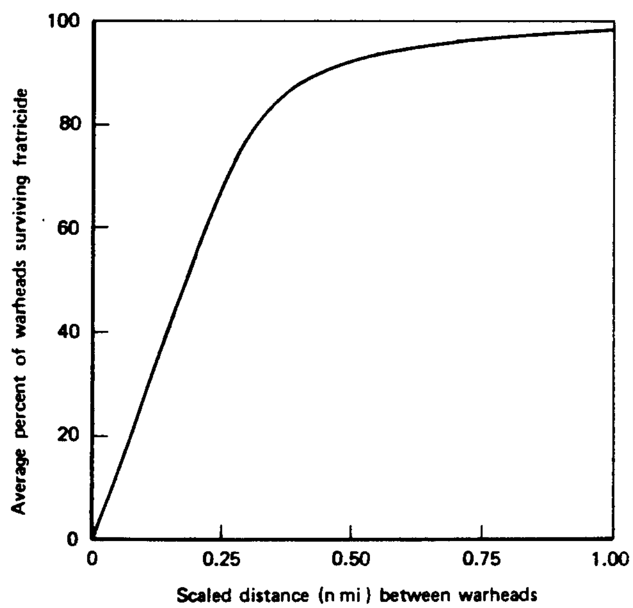

Fig. 43—Average fratricide assumed along a trench

CHANGING THE CONFIGURATION OF ATTACKING ICBMS

As both the United States and the Soviet Union have shown in their choices of MIRV systems, any given ICBM payload can be con-

[9]This limit also holds for variations in MIRVing, as will be discussed shortly. It maintains a fair amount of survivability in trenches as opposed to the other two systems, which face no such limit, and therefore may tend to bias survivability calculations in favor of trenches, as will be noted below. However, App. E shows that this approximation may partially reflect the physical phenomena involved in fratricide.

figured in quite a number of ways.[10] The basic tradeoff in such configurations is an increase in the number of warheads at the cost of a decrease in yield per warhead. Increasing the number of warheads also decreases the *total* yield carried in a given payload, because extra weight must go into the housing and shielding of each warhead, and into providing other support for that warhead (such as fuel in the warhead bus to provide for a different trajectory for that warhead). For example, by the mid-1980s, a Soviet SS-18 may deliver a single 25-megaton warhead, or eight 1.5-megaton warheads with a total yield of 12 megatons.[11] To parameterize "MIRV tradeoffs," this SS-18 tradeoff was assumed to be standard, and it was further assumed that total yield decreased at a constant percentage for each extra warhead added. Thus, according to the above SS-18 data, each warhead added reduces total yield by about 10 percent.[12] Having calculated the total yield for a given number of warheads per ICBM, the yield of each warhead is then easily determined. Such MIRV tradeoff curves are shown in Fig. 44[13] for the three Soviet MIRVed ICBM systems based upon a 10-percent loss of total yield per warhead added, and using as a base the 25-megaton single warhead for the SS-18, six one-megaton warheads for the SS-19, and four 600-kt warheads for the SS-17.[14] Naturally, these curves do suggest different tradeoffs: an SS-18 may carry twice as many 10-Mt warheads as does an SS-19, but only about 30 percent more 100-kt warheads than does an SS-19. While these curves may be somewhat inaccurate (especially below one megaton,

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[10]Some examples of MIRV tradeoffs are given in Mason Willrich and John B. Rhinelander, *SALT: The Moscow Agreements and Beyond*, The Free Press, New York, 1974, pp. 46-48; see also *U.S.-USSR Strategic Policies*, pp. 6-7. The latter source gives numbers fairly close to those shown in Fig. 44. Willrich and Rhinelander quote numbers lower than these curves, however, and Robinson, "SALT Agreements Face Trouble in Congress," *Aviation Week and Space Technology*, October 17, 1977, quotes a single number on p. 15 that is higher (45 70-kt warheads for an SS-18).

[11]Robinson, "MX Deployment Urged for Parity," pp. 14-15.

[12]Thus, the 12 total megatons of the eight-warhead configuration or the 25 megatons of the one-warhead configuration can be obtained from:

$$TY_{18} = 25 \cdot (0.9)^{m-1}$$

where TY_{18} is the total yield and m is the number of MIRVed warheads per SS-18.

[13]A curve that is very similar for an SS-19 is shown in Foster, p. 36. Differences exist primarily for configurations of more than ten warheads, which is more clearly a speculative range for the formulation herein, since it goes beyond present designs. Further, the SALT II Treaty, if ratified, would prevent either side from placing more than ten warheads on any ICBM.

[14]Robinson, "MX Deployment Urged for Parity," pp. 14-15. The SS-19 value is for 1985, while those of the SS-17 and SS-18 are for the early 1980s, since no specific 1985 values are given for them. The large differences between the SS-17 and the SS-19 shown here (based upon Robinson's numbers) are difficult to understand, given that these two missiles are supposed to have about the same payload.

where we do not have an SS-18 MIRV value to verify the 10-percent marginal loss in total yield), they do provide a possible representation of the potential tradeoffs.

The potential of changing the warhead configuration is important because it can often improve the effectiveness of the attacking force. For example, in the attack on shelters above, only 4200 of the 6000 total shelters are hit with a warhead, yet each warhead is more than large enough to destroy its target. Therefore, by moving to more and smaller warheads, a higher percentage of the 6000 total shelters can be attacked and destroyed. Using the curves of Fig. 44, the effect of different warhead configurations can be found, and an optimum configuration determined for each kind of attack. Since the MIRV tradeoff curves of Fig. 44 vary a fair amount, this process will be simplified herein by using only the SS-19 curve as a single estimate of the tradeoffs. In doing so, the nominal 4200 one-megaton warhead attack is equivalent to an attack by 700 SS-19 missiles.[15]

Figure 45 shows the potential ICBM survivability, given that the Soviet force could make these tradeoffs. The MIRV option in each case is represented by the individual warhead yield shown on the x-axis. For the silos, the one-megaton configuration is a smaller yield than optimal because many warheads are used per silo, most being destroyed by fratricide; fewer warheads of a higher yield have a higher SSPK and are not wasted by fratricide (if fratricide actually occurs as modeled). Still, the difference in PK is not very great. The one-megaton yield, however, is greater than optimum for both trenches and shelters.[16] As argued above, the attack against shelters does much better when more warheads are available to cover every shelter, even though the warheads are somewhat smaller. For still smaller warheads, the opportunity of placing a second warhead on some shelters does not offset the loss in yield required to do so. Therefore, the optimum configuration is nine 500-kt warheads (6300 total), with a PK slightly more than 85 percent. For the trench, the same smaller warhead configuration does slightly better than the one-megaton

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[15]Most studies place the Soviet mid-1980s ICBM threat at about 5000 to 6000 one-megaton warheads. For example, Steinbruner and Garwin, p. 150, give the number of 5400. A similar estimate of 5440 is obtained by using the tradeoff curves of Fig. 44 and the number of systems in Robinson, "MX Deployment Urged for Parity," pp. 14-15. Of these, 600 come from SS-17s (200 missiles times 3 one-megaton warheads), 2460 from SS-19s (410 missiles times 6), 2080 from SS-18s (208 missiles times 10), and 300 from a non-MIRV missile (SS-11?). This excludes 100 SS-18s that would, theoretically, retain a single 25-megaton warhead. Thus, 4200 warheads are about three-quarters of this total threat.

[16]Should the United States deploy an MPS system like either alternative analyzed here, this relationship implies that the Soviets would have strong incentives to reconfigure their ICBMs to smaller MIRVs, a costly process but one that could change the results of any of our nominal calculations.

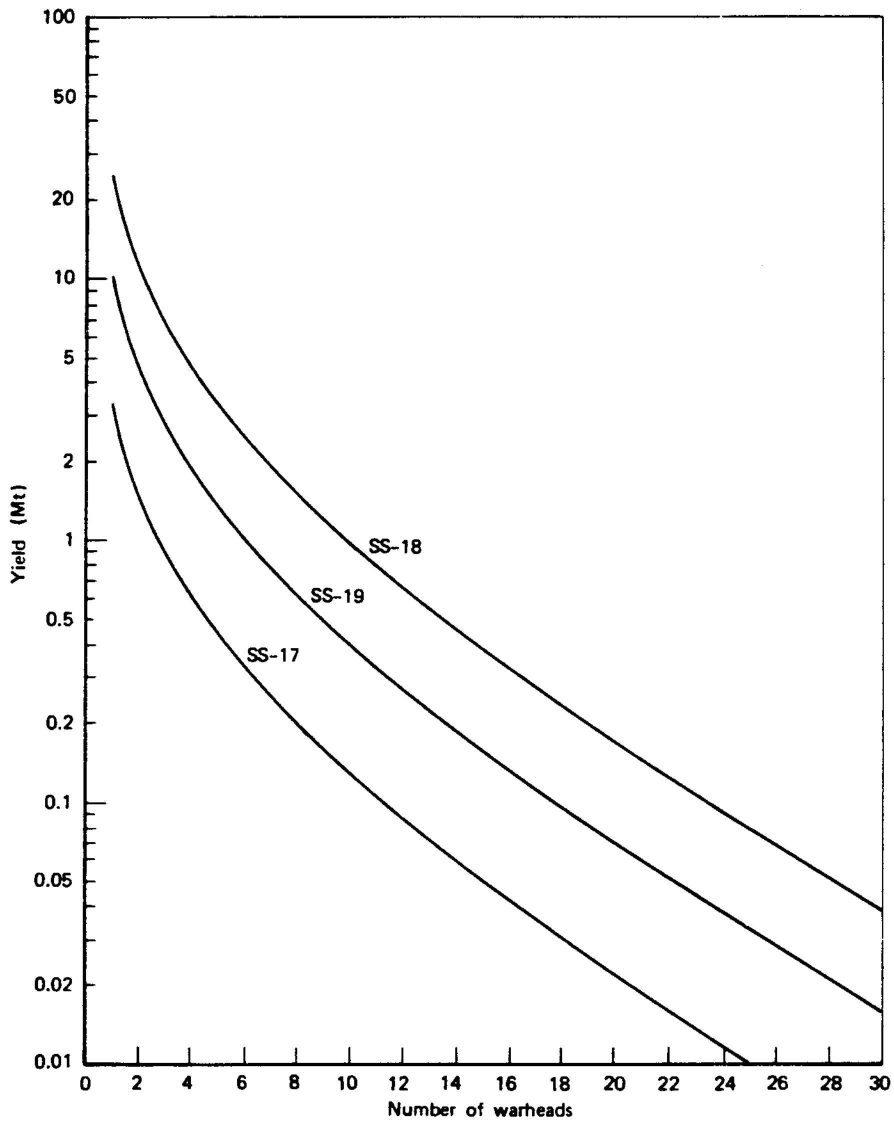

Fig. 44—MIRV tradeoff curves

warheads, apparently causing a more optimum distribution of effects along the trench. The optimum PK here, though, is not quite 65 percent, barely better than the 60-percent PK at one megaton. This is a normal pattern: For basic attack sizes that cover less than all of the U.S. missile shelters, survivability can improve significantly with a change in the MIRV configuration to more and smaller warheads; but the survivability of a trench does not tend to be anywhere near as sensitive to warhead configuration.

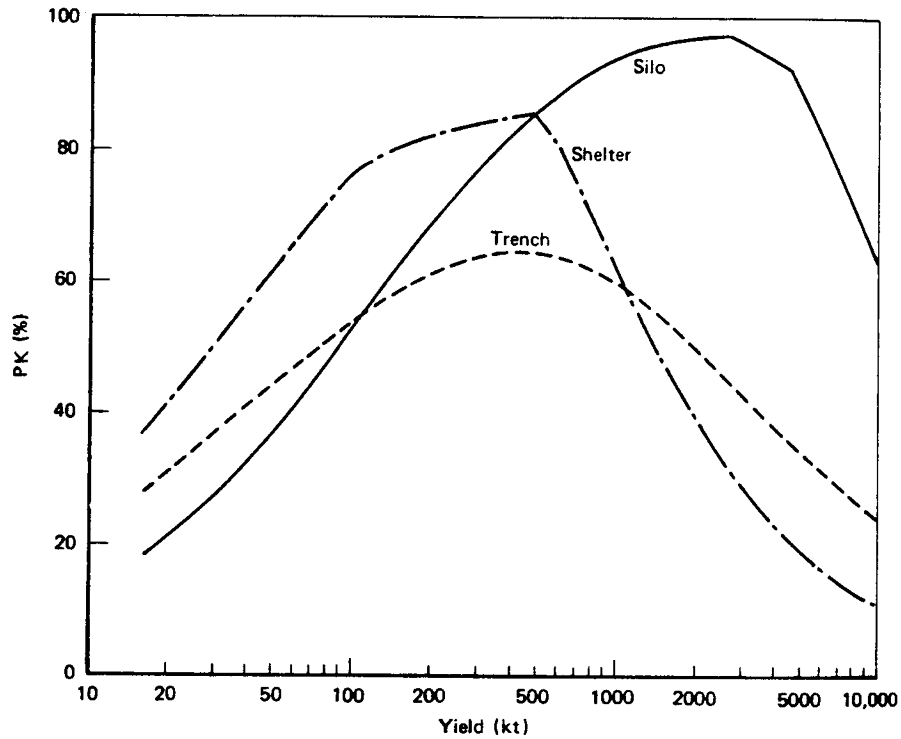

Fig. 45—Basic attack on different basing modes for different Soviet warhead configurations

It is also important to note that the ability to change warhead configuration can influence the sensitivity of PK to changes in the other parameters. This is shown for changes of CEP in Fig. 46, where the optimum configuration is used at each value of CEP to calculate the PK. In this case, the shelters are clearly most sensitive to changes,

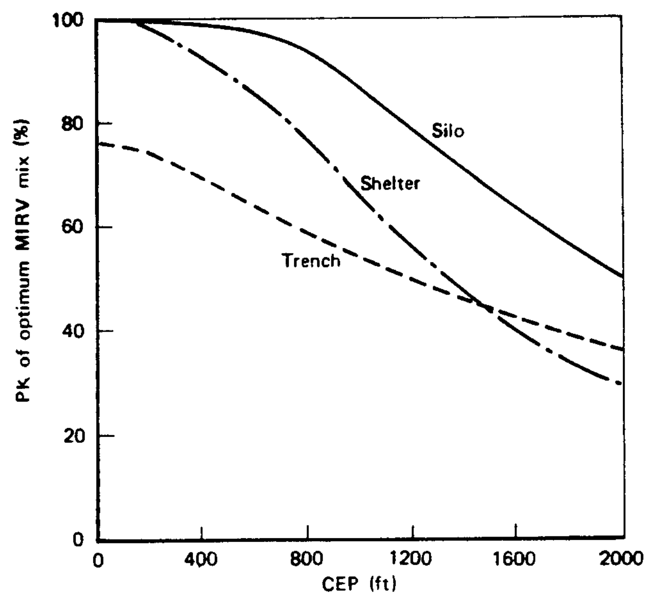

Fig. 46—PK for optimum warhead mix at different CEPs

and dramatically more so than they are for a fixed CEP as shown in Fig. 40. Trenches are also more sensitive here, especially in the lower CEP ranges, since yield does not have to be used to compensate for accuracy, and thus smaller warheads can be used. Silos are less sensitive to CEP changes when warhead mix can be altered, since the use of fewer, larger warheads offsets some of the inaccuracy for large CEP values. Figure 47 presents the optimum configuration used in each case, showing that the optimum number of warheads is much more variable when attacking shelters than trenches or silos once CEPs become less than 600 feet. Naturally, the Soviets' ability to employ such configurations may be severely limited by the ten-warhead-per-ICBM constraint in the proposed SALT II Treaty, though some tradeoffs might still be possible.

This aspect of the warhead mix complicates the uncertainty problem for the attacker, since he must choose a warhead configuration before the attack and before he is able to resolve his uncertainties. As shown in Fig. 45, a choice that misses the optimum on either side by

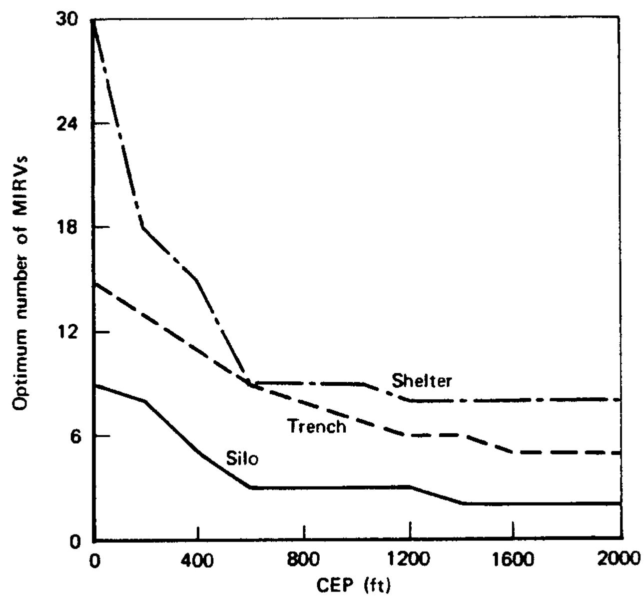

Fig. 47—Number of SS-19 warheads optimum at different CEPs

a small amount is not too costly, but larger errors can cost the attacker significantly in effectiveness (except, perhaps, against trenches), and the optimum configuration can differ for different basing schemes. Therefore, in designing his force, the attacker must guess at the probable target set he will face and the performance of his own system, and perhaps hedge somewhat against the uncertainties. The attacker's choice of warhead configuration therefore may tell the defender a great deal about how the attacker expects to use his forces and how he expects them to perform.

In examining MIRV calculations in Sec. IV, it was noted that accuracy and reliability values can degrade for warheads after the first on each missile. While it was shown that such degradations would not be very significant for an eight-warhead missile, this is not as true for missiles using many more warheads. Using the same degradations,[17] Fig. 48 shows the modified effect on PK of changes in CEP, and Fig. 49 shows the modified optimum warhead

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[17]These degradations were a 25-foot increase in the nominal CEP and a one-percent decrease in the nominal reliability for each warhead after the first.

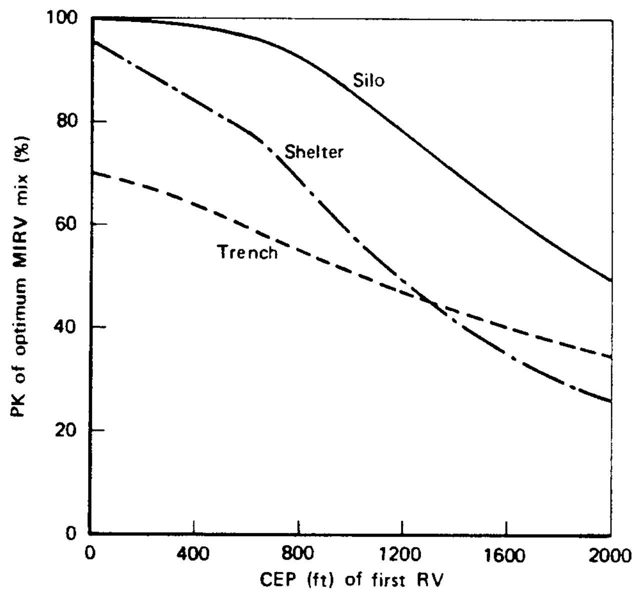

Fig. 48—PK for optimum MIRV mix allowing for CEP and reliability degradation

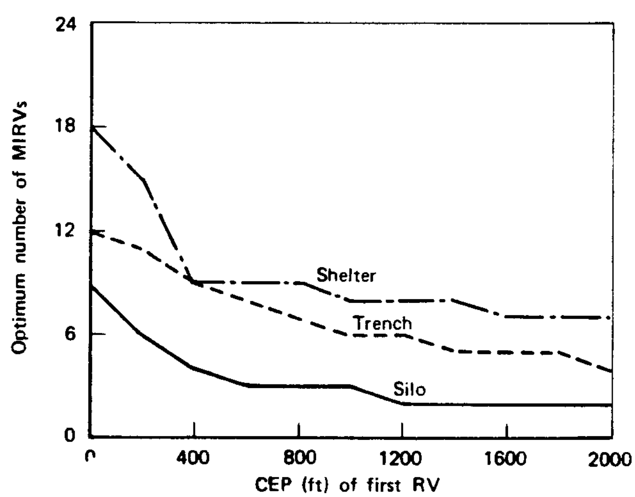

Fig. 49—Number of warheads optimum at different CEPs allowing for CEP and reliability degradation

configurations. While these degradations have only a slight effect on silo or trench survivability, the shelter survival changes significantly, especially for small values of the initial CEP; the optimum number of warheads per missile also decreases sharply for small CEPS (in line with the maximum of ten in SALT II until very good accuracies are achieved). The potential effect of accuracy and reliability degradations, then, is much greater as accuracy becomes better than the nominal 600-foot CEP, especially if the attacker can reconfigure his missiles and the defender uses a shelter basing system.

DECEPTION FAILURE AND OTHER ATTACK MULTIPLIERS

Several factors beyond those discussed above can influence the survivability of an MPS system, not all of which affect silo survivability. The most important is the success of the deception scheme in preventing the attacker from being able to localize the missile. If the attacker can determine that a particular small portion of the MPS system does not contain any missiles, he can ignore it, concentrate his warheads elsewhere, and obtain a higher kill probability. To parameterize this effect, the fraction of the MPS system discovered by the attacker not to contain a missile will be referred to as E (empty).[18] The defender, however, may decide during deployment that the MPS system originally envisioned is too expensive, and therefore lowers the number of shelters to cut costs; the effect is basically the same as that discussed above. The symbol R (retained) will be used to represent the percentage of the planned system (6000 shelters, 3600 nautical miles of trench) remaining after such a cut.[19] Finally, the Soviets could increase their attack size by a reallocation of ICBMs not previously committed, by reuse of ICBM launchers, or by ICBM breakout or cheating (deploying additional missiles covertly). This change, the only one that would affect the outcome of an attack on silos as well, will be represented by S (attack size). For MPS systems, these factors can be integrated into an attack multiplier, M:[20]

[18]In reality, an attacker must be virtually certain that this fraction of the MPS system (E) contains no missiles. If he instead simply believes that this fraction has a lower probability of containing missiles than the rest of the system, then his calculation becomes considerably more complicated, as shown in App. F.

[19]For the change from the nominal 6000 shelters shown here to the present MX plan of 4600, R = 0.77.

[20]For silo systems, M = S. This S, the attack size multiplier, may vary with the Soviets' reaction to different U.S. policy choices.

$$M = \frac{S}{(1 - E) \cdot R}$$

For example, if the Soviets increased their attack size by 20 percent, ascertained that a specific 20 percent of the MPS system definitely did not contain missiles, and the United States built only 80 percent of the nominal MPS system, then:

$$M = \frac{1.2}{(1 - 0.2) \cdot 0.8} \doteq 1.9$$

In other words, these three factors can quickly compound into a substantial attack multiplier.

Figure 50 shows the effect on ICBM survivability in the different basing modes for an attack multiplier of two. In comparison with the basic attack results shown in Fig. 45, this figure shows much higher values of PK, and also a shift in the optimum warhead configurations toward a higher yield.[21] The higher values of PK in Fig. 50 indicate, in particular, that even an MPS system may not, on the average, be very survivable if the Soviets are able to overcome some of the U.S. attempt at deception, and/or bring some more assets to bear in the attack.

The potential extent of the attack multiplier's effect is shown in Figs. 51 and 52. In Fig. 51, the attack multiplier is applied at the optimum warhead configuration (assuming the nominal attack data), yielding a 90-percent value for PK at $M = 0.45$ for silos, and at $M = 1.3$ for shelters. At a multiplier of two, neither shelters nor silos are, nominally, very survivable. In these calculations, the PK against the trench system never rises above 86 percent because of the effect of the trench fratricide model (as explained above); still, a force multiplier of two or three places the trench PK up at this maximum.

In Fig. 52, only the one-megaton warhead configuration is used, producing nearly the same results, though not giving quite as high values in most cases. The silo system reaches the 90-percent value of PK again at about $M = 0.45$, though the one-megaton warhead is too small to drive the PK value over about 94 percent (assuming all warheads are groundburst), no matter how big the attack multiplier becomes (since, as M gets larger, almost all of the extra warheads are lost to fratricide as modeled herein). The shelter system reaches a 90-percent value of PK at $M = 1.65$ for one-megaton warheads, so that by $M = 2$ the PK is once again very high. Finally, the trench takes on roughly the same form as in the optimum configuration, since one-

[21]Interestingly, as noted above, a Soviet change in warhead configuration in this direction might well signal their perception of such an attack multiplier.

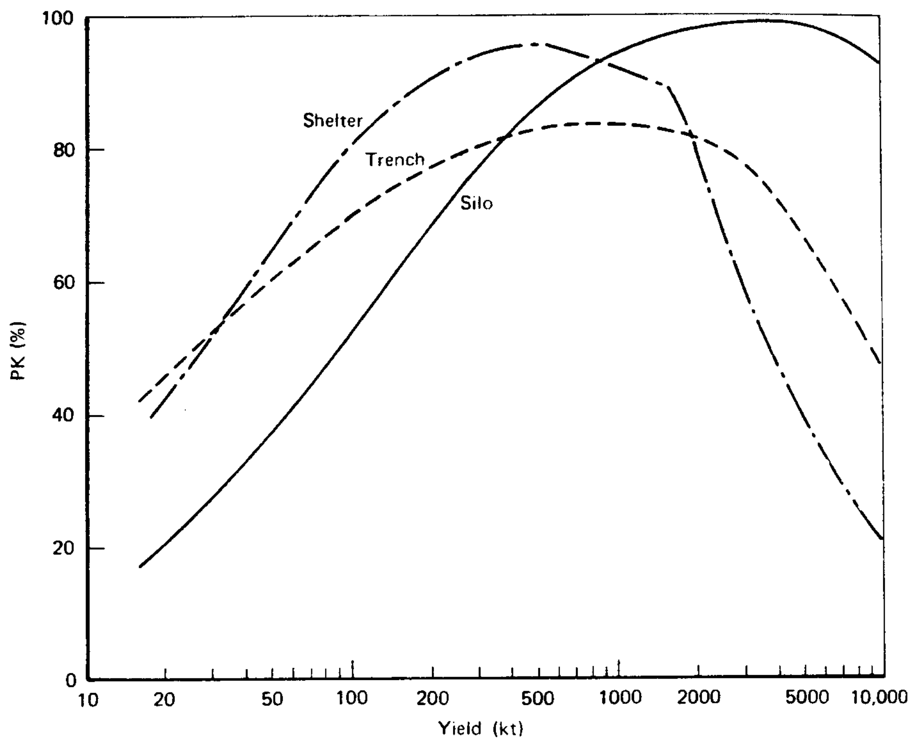

Fig. 50—Effect of an attack multiplier of two on different basing modes

megaton warheads are always close to optimum throughout its range. It is significant to note that, in either of these figures, the early part of these curves (below M = 1) rises very sharply, making the kill probability *very sensitive* to the attack multiplier (and, as a result, to any uncertainty in it). Thereafter, the curves are not nearly as sensitive, but in this range PK is very high. In other words, a high value of the attack multiplier (above one) serves both to increase PK and decrease uncertainty for the attacker.

At this point it is appropriate to note that the actual uncertainty in MPS survivability is inherently greater than that involved in silo survivability. In the case of a silo system, the analysis focuses on an already deployed target system and a weapon system that is a simple modification of those presently being deployed by the Soviets. In talking about MPS systems, we are talking about a world where even the

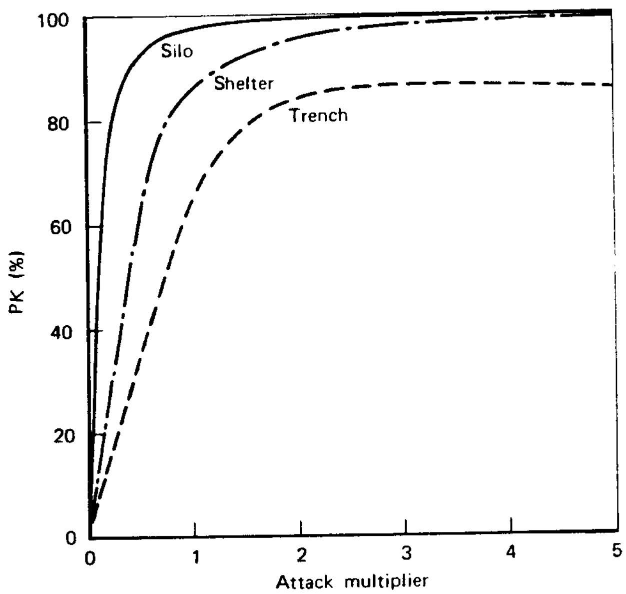

Fig. 51—Effect of attack multiplier on PK for optimum warhead configuration

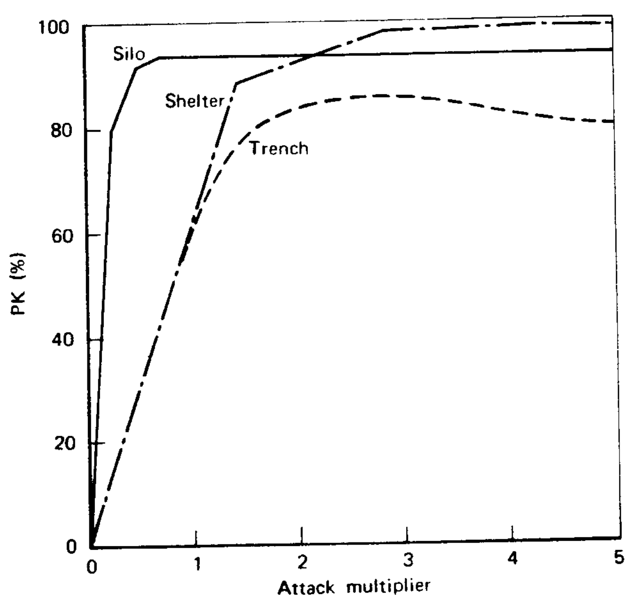

Fig. 52—Effect of attack multiplier on PK for fixed 1-Mt warheads

design of both weapons and targets is uncertain. Naturally, once both are deployed, much of this extra uncertainty will disappear; but for now, in trying to project into the late 1980s when such a system could be deployed, this extra uncertainty in design and deployment cannot be ignored. To help compensate for this uncertainty, the force multiplier will be entered into the complete assessment below as an uncertain parameter.

TOWARD A NET ASSESSMENT OF ICBM BASING OPTIONS

Based upon the relationships developed above, it is possible to show how to analyze the relative merits of each basing option. This analysis should *not* be treated as a definitive assessment, for three reasons: (1) It is based solely upon the values of parameters given in *Aviation Week* and developed elsewhere herein, (2) it assumes that the nominal parameter values are perceived as being the same by both the attacker and defender (which, though unlikely, is a hard assumption to avoid), and (3) it uses a methodology which, though fairly complex, still simplifies many of the relationships for ease of calculation. Rather, this analysis should be treated as a pattern for future efforts. The focus here, accordingly, is not on making policy conclusions but on the methodology used to reach those conclusions.

Figures 53 and 54 compare the relative possible survivability of the three basing options. The distributions are based upon the uncertainty parameters developed above, as well as upon some specific assumptions about uncertainty in the force multiplier.[22] These calculations also assume that the Soviets reconfigure their warheads for attacks on shelters only, using the 500-kt warhead option, which is clearly much closer to optimum. Finally, because trenches as a structure involve much greater uncertainties in hardness (since tubes tend to amplify shocks),[23] the standard deviation of the vulnerability number for trenches was doubled for both sides.

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[22]The attack size is assumed to be 4200 warheads, with a standard deviation of 10 percent from the Soviet view and 25 percent from the U.S. view. As noted above, this is the only factor that affects the attack multiplier for silos. For shelters and trenches, the percent of the system assumed to be empty is taken as 20 percent, with a 10-percent standard deviation for both the United States and the Soviet Union. Finally, the actual size of the MPS systems is as given above (R = 1), with a 20-percent standard deviation from the Soviet point of view and a 10-percent standard deviation for the United States. This analysis also assumes that the trench and shelter systems are equivalently affected by these factors.

[23]See, for example, the calculations in Charles E. Needham and Cydney Westmoreland, *Airblast Calculations for Advanced Missile System (MX) Support*, Air Force Weapons Laboratory, AFWL-TR-75-297, February 1976, especially pp. 8-17.

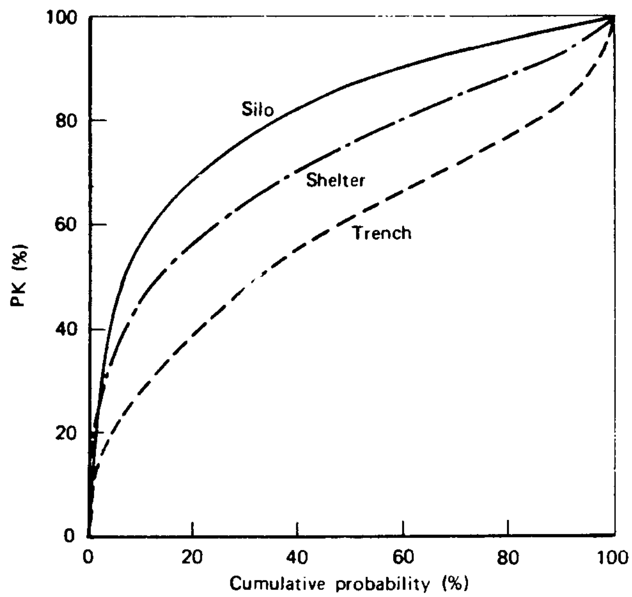

Fig. 53—High U.S. uncertainty in ICBM survival for three basing modes

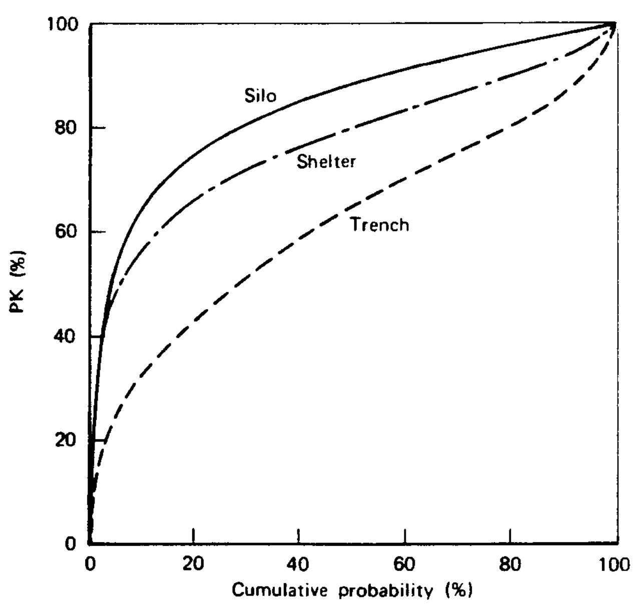

Fig. 54—High Soviet uncertainty in U.S. ICBM survival for three basing modes

From both the U.S. and Soviet points of view, this assessment shows trenches to be the most survivable, shelters to be the next most survivable, and silos to be the least survivable. The relative degree of survivability may be surprising, however. Especially from the Soviet point of view, this assessment of the shelter system indicates that it may not be a great deal more survivable than the present silo system (with a PK at most 9 percent less). The difference is rendered that small partly by allowing the Soviets to reconfigure their warheads (which they could do rather easily, especially if not constrained by SALT II); otherwise, the shelter curve would be close to the trench curve. Naturally, if more shelters per missile were used (25 or 30 instead of the nominal 20), the shelter system would prove more survivable, though another change in warhead configuration might well offset much of this improvement, as suggested by the slope of the curve in Fig. 51.

The trench curve, by contrast, shows trenches to be very much more survivable than silos, assuming the nominal attack and uncertainty data (especially the trench fratricide model). Indeed, according to this assessment, trenches should be about twice as survivable as silos. Trenches are that highly survivable because, as shown above, they are not very susceptible to changes in warhead configuration by the attacker, and thus the notion of aimpoint proliferation does indeed hold. This assessment, however, assumes a fratricide model that limits the nominal PK against a trench to 86 percent; should a different pattern of fratricide hold, the trench PK *could* increase, and a change in warhead configuration *could* become more profitable.[24] Further, trenches may be more susceptible to Soviet attempts to overcome the deception. For example, a sensor placed at the center of a trench that simply indicated which half of the trench contained the missile would lead to an attack multiplier of at least two, making trenches considerably less survivable than shown here. Therefore, while a trench system appears to be significantly more survivable than the other two forms of basing, this finding is based upon assumptions (such as the fratricide model and successful deception) that probably bias the results in favor of trenches.

For all three basing modes, the uncertainties shown in these figures are substantial. From the point of view of both defender and attacker, little confidence can be had in the outcome of such an attack. In this situation, the attacker would undoubtedly desire to reduce some of these uncertainties so that he could be more confident of his attack. Yet, even if we deal with the silo attack, in which he does the

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[24]Actually, making the change to the 500-kt warheads, as was done with shelters, should increase the trench PK a few percent in any case, as shown in Fig. 45.

best, reducing the uncertainties is not an easy task. This is shown for the Soviets in Fig. 55, where the "basic uncertainty" curve excludes uncertainty in accuracy (CEP and bias), reliability, attack multiplier, fratricide, weapon radius, and vulnerability number. This amount of uncertainty may be acceptable to an attacker; it certainly is much less than the uncertainty shown in Fig. 54. Many of the uncertainties, however, such as fratricide, may be absolutely impossible to resolve (with an atmospheric test ban in effect), and some, such as systematic bias and the deception multiplier,[25] may be almost impossible to resolve. Therefore, this "basic uncertainty" level is probably not attainable. Figure 55 also shows the relative effect of being able to reduce the uncertainty in accuracy and reliability on the one hand, and in fratricide, attack multiplier, weapon radius, and vulnerability number ("basic plus accuracy and reliability uncertainty") on the other. Either of these curves introduces a substantial, probably unacceptable (to the attacker), amount of uncertainty in the PK. In comparison with the complete uncertainty curve, as shown in Fig. 56,

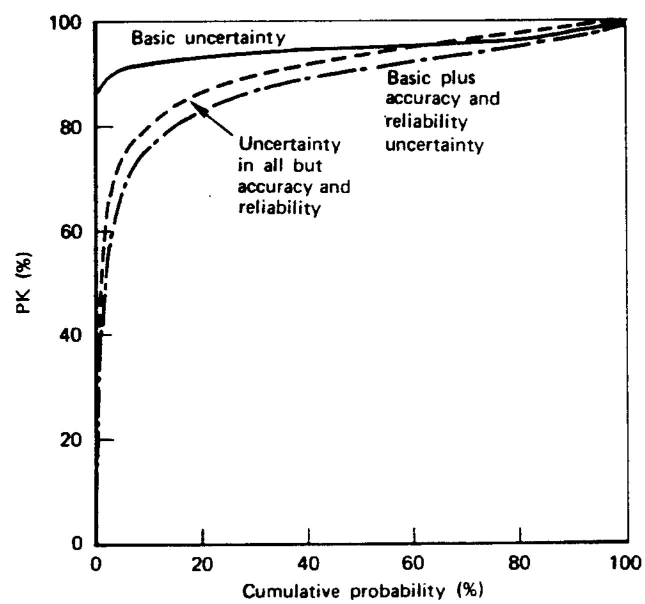

Fig. 55—High Soviet uncertainty in U.S. ICBM survival; effect of suppressing some uncertainties

[25]That is, the Soviets would never be quite sure that their assessment of missile locations is correct.

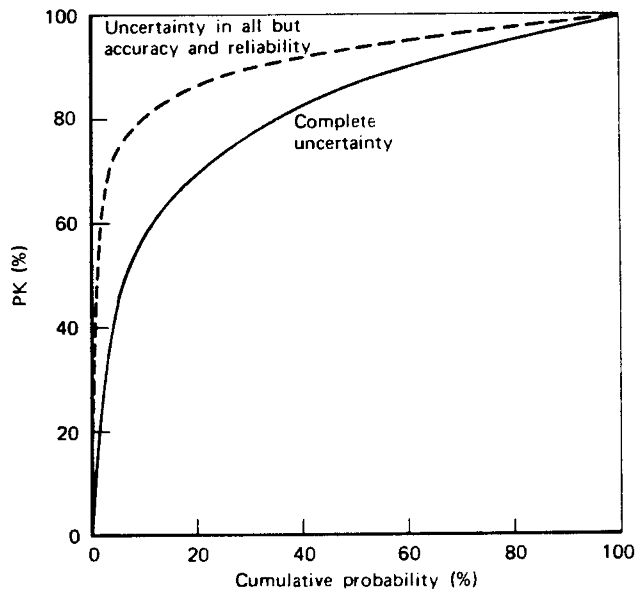

Fig. 56—High Soviet uncertainty in U.S. ICBM survival; relative effect of suppressing some uncertainties

these are major changes in the level of uncertainty, but since they still represent high risk, and since the attacker is unlikely to be able to obtain even this degree of uncertainty reduction, uncertainty in survivability is likely to dominate these calculations in spite of any efforts by the attacker to resolve individual uncertainties.

CONCLUSIONS

Uncertainty in ICBM survival is very large for both present and future ICBM basing options. That uncertainty makes it impossible for an attacker to obtain any standard level of confidence in his ability to destroy U.S. ICBMs. This uncertainty also affects the U.S. choice of an alternative basing mode, and the sensitivity of those options to various system changes that the attacker could make. Because of the importance of this uncertainty in survival, the methodology developed here presents a useful point of departure for future assessments of ICBM survivability.

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